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Proton capture on stored radioactive ^{118}Te ions

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Abstract. Experimental determination of the cross sections of proton capture on radioactive nuclei is extremely difficult. Therefore, it is of substantial interest for the understanding of the production of the p-nuclei. For the first time, a direct measurement of proton-capture cross sections on stored, radioactive ions became possible in an energy range of interest for nuclear astrophysics. The experiment was performed at the Experimental Storage Ring (ESR) at GSI by making use of a sensitive method to measure (p,γ) and (p,n) reactions in inverse kinematics. These reaction channels are of high relevance for the nucleosynthesis processes in supernovae, which are among the most violent explosions in the universe and are not yet well understood. The cross section of the ^{118}Te(p,γ) reaction has been measured at energies of 6 MeV/u and 7 MeV/u. The heavy ions interacted with a hydrogen gas jet target. The radiative recombination process of the fully stripped ^{118}Te ions and electrons from the hydrogen target was used as a luminosity monitor. An overview of the experimental method and preliminary results from the ongoing analysis will be presented.

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1 Astrophysical motivation

Most of the elements heavier than iron are synthesized by neutron-induced reactions. However, there are around 35 stable neutron-deficient nuclei which cannot be made by either the s process or the r process. The understanding of the production of these so called p-nuclei is a current challenge in nuclear astrophysics. They have the lowest relative abundance and their production cannot be described by neutron capture processes. A production process that is currently considered to be likely to create the majority of p-nuclei is the γ process [1, 2]. By photodisintegration of pre-existing seed nuclei and subsequent β decays, p-nuclei may be produced. Simulations of the γ process involve several thousand nuclei that are connected by tens of thousands of reactions. It requires correspondingly large reaction networks to model the abundance distributions that follow from these scenarios [3]. Given the low cross sections at energies of interest for nuclear astrophysics, limited experimental data for proton capture reactions are available. Additionally, the majority of the involved nuclei are unstable, since the γ-process nucleosynthesis path moves far from the valley of stability. Experimentally there is nearly no data available, so the calculations are affected by large uncertainties [1, 2, 4, 5]. However, it is of utmost importance that these calculations are based on experimentally determined data. The measurement of a (p,γ) cross section provides, besides the determination of a (p, γ) reaction under stellar conditions, the determination of the inverse (γ,p) reaction rates, that are important for the γ process models. ^{118}Te is part of the γ process network and was chosen for these first radioactive beam studies for feasibility reasons as well as for the ability to achieve high intensities. With this experiment, for the first time a proton capture was successfully performed on stored radioactive ions in an energy region relevant for p-nucleosynthesis.

2 Experimental realization at the Experimental Storage Ring (ESR) at GSI

This experiment has become possible at GSI, by combining two unique facilities, the Fragment Seperator (FRS) [6] and the Experimental Storage Ring (ESR) [7]. In a classical nuclear reaction measurement a light projectile impinges on a heavy target, but if the target is radioactive and short-lived a sample can not be prepared. The desired nuclei must be produced online during the experiment. The study is then done in inverse kinematics. Due to the use of a radioactive isotope, with a half-life of 6 days in the case of ^{118}Te, a measurement in inverse kinematics is necessary. Due to the expected small cross sections, especially in the relevant energy range, very small counting rates are expected. Heavy ion storage rings like the ESR can compensate for low reaction rates and enable for the use of thin targets accompanied by low energy losses of the projectiles. Due to multiple passages of the projectile through the target, luminosities comparable to single pass experiments with thick targets can be achieved. By impinging stable ^{124}Xe ions on a Be production target a variety of fragments were produced, among them the radioactive isotope ^{118}Te. By magnetic separation combined with energy losses in dedicated energy degraders it was possible to filter out a clean beam of ^{118}Te in the FRS. Afterwards, ^{118}Te was stored in the ESR at 400 MeV/u. By accumulating up to 20 injections from the FRS, high beam intensities could be achieved. Inside the ESR, the fully-ionized ions were cooled and decelerated down to 6 and 7 MeV/u providing about 10^6 ions for the measurement [8]. By collisions of the radioactive beam and a thin hydrogen gas jet [9] target, proton capture reactions could take place. A proof-of-principle experiment had been performed in 2009 [10] for ^{96}Ru(p,γ) and an improved setup was introduced in 2016 to validate the method with ^{124}Xe(p,γ) close to the astrophysical Gamow window [11].

To determine the cross section in a conventional way, the number of ions inside the ring as well as the target density would have to be known exactly. The determination of these would only be possible with large uncertainties. It is therefore of significant advantage to measure the cross section relative to a well understood simultaneously occurring process. The cross section for the proton capture process is determined relative to that of the radiative electron capture (REC) of electrons from the hydrogen atoms into the bare Te ions. To measure the emitted photons X-ray detectors were used in this experiment [12]. The cross section is derived by:

$$\sigma_{(p,\gamma)} = \frac{N_{(p,\gamma)}}{N_{K-REC}} \epsilon_{K-REC,intr} \int_{\Delta\Omega} \frac{d\sigma_{K-REC}}{d\Omega} d\Omega \quad . \tag{1}$$

Here, $N_{(p,\gamma)}$ describes the number of protons captured, N_{K-REC} the number of emitted photons after electrons capture in the K-shell and $\epsilon_{K-REC,intr}$ the efficiency of the X-ray detectors used. The angle dependent cross section $\int_{\Delta\Omega} \frac{d\sigma_{K-REC}}{d\Omega} d\Omega$ of the radiative electron capture into the K-shell can be predicted very accurately by theory [13]. Figure 1 shows an X-ray spectrum that has been taken during the experiment with a High Purity Germanium (HPGe) detector installed at an angle of 90°. Highlighted in red is the corresponding peak for photons emitted after an electron is captured directly into the K-shell of the ^{118}Te projectiles.

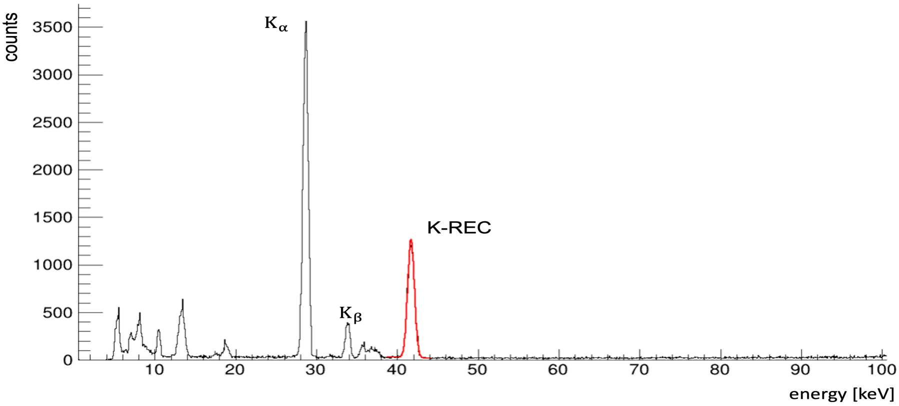

Figure 1. X-ray spectrum recorded by a HPGe detector positioned at an angle of 90° at the target region. The peak corresponding to the photons emitted after an electron is captured into the K-shell of the ^{118}Te projectiles is marked in red.

In order to determine the number of reaction products, they must be detected separately from the stored beam and the background. A dipole magnet behind the target section provides magnetic separation between the emitted reaction products and the stored beam. The bending radius ρ of an ion within a homogeneous magnetic field B can be derived from the equivalence of acting Lorentz and centripetal force:

$$B\rho = p/q \tag{2}$$

After a proton capture, the momentum p remains almost unchanged whereas the charge q increases by 1e. This leads to a decreased bending radius. The reaction products thus shift to the inner side of the ring. By placing a detector at the inner side of the ring the reaction products can be observed. For this measurement, a Double Sided Silicon Strip Detector (DSSSD) was used, consisting of 16 x 16 strips in x and y directions, respectively. This allows for an exact determination of the number of the incident reaction products. Figure 2 shows the ion hit distributions that have been measured with the DSSSD during the experiment. The left plot shows data that has been taken with ^{118}Te at 7 MeV/u for 48 h and the right plot for 52 h with an energy of 6 MeV/u.

Due to the small nuclear cross sections, proton capture at the target occurs only rarely. In contrast, many ions undergo scattering off the target atoms. The dominant process is Rutherford scattering, which results in a large background contribution [14]. Due to the divergence of the cross sections of Rutherford scattering and proton-capture towards lower energies, the peak-to-background ratio becomes worse at low energies. This relation could be improved drastically by the usage of a scraper based ERASE technique [15], that physically blocks the disturbing Rutherford distribution, while leaving the proton-capture products untouched. This has made it possible to reach energies of 6 MeV/u for this experiment.

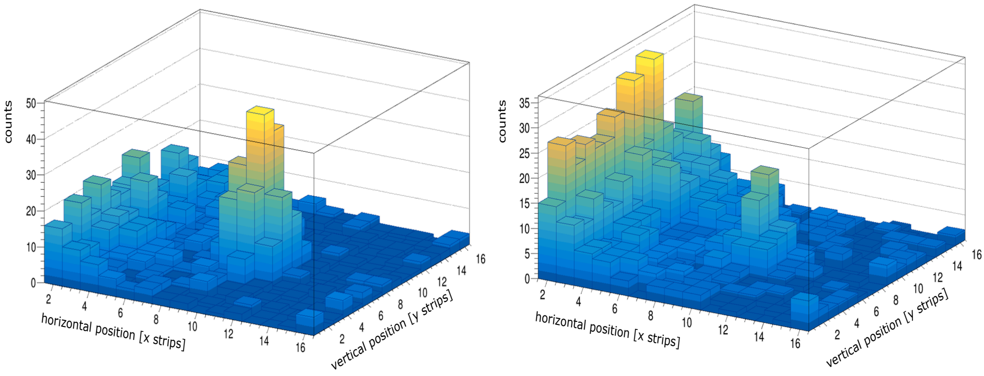

Figure 2. Hit distribution taken with the DSSSD. The left plot shows data for ^{118}Te at 7 MeV/u that has been taken for 48 h and the right plot shows data of ^{118}Te at 6 MeV/u taken for 52 h.

This enables the determination of the number of events by integrating over the peak. To subtract the background in the region of the peak, currently a special fit is used. The fit of the entire spectrum includes a 2D Gaussian fit for the peak and an additional 2D Gaussian fit for the background. In order to achieve a more precise description of the data simulations are in progress. For this purpose, a Monte Carlo simulation code will be used, namely MOCADI, a code developed at GSI [16].

3 Preliminary results

The conducted analysis provides the first preliminary constraints from experimentally determined cross sections. The preliminary cross sections have expected uncertainties of less than 5 %. Figure 3 shows the experimentally determined cross sections from this work and for an energy of 10.05 MeV [15]. The center of mass energy is plotted on the abscissa. Additionally, the theoretical predictions by NON-SMOKER [17] are shown in blue, as well as the predictions by the TALYS code [18] shown in green. The results seem to deviate from the theory for lower energies, whereas for higher energies the values agree within the uncertainties, with the predictions by NON-SMOKER. Since these are still preliminary results, this may be subject to further adjustments.

Further uncertainty calculations as well as simulations for a more precise determination of the background in the region of the peak are the main outstanding tasks.

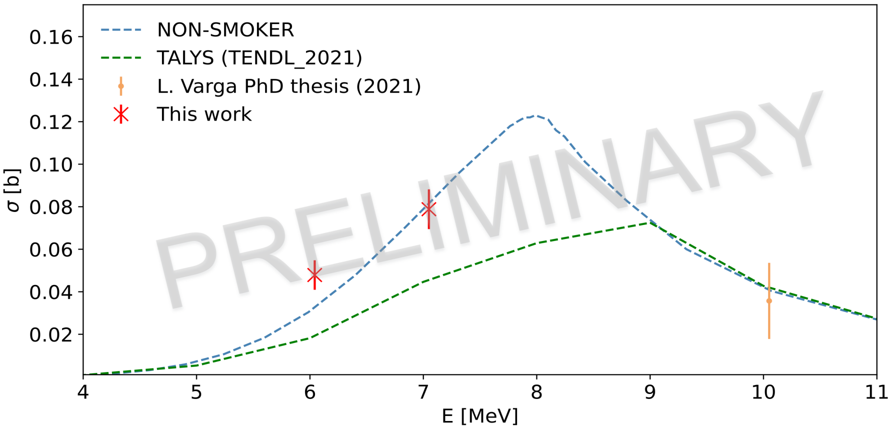

Figure 3. Preliminary cross sections obtained in this work in comparison with theoretical predictions.

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