Partial cross sections of $^{181}$Ta(n,γ) using BEGe detectors

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Abstract. Heavy nuclei are mainly synthesised by a sequence of neutron captures and β-decays. The corresponding neutron energies in the different astrophysical sites range from 1 keV to 1 MeV. By using the activation technique, small neutron capture cross sections can be studied. A sample is irradiated by a quasi-stellar neutron spectrum in order to produce radioactive isotopes. The decay of the radioactive nuclei can be detected by their characteristic gamma rays. For this purpose, sensitive experimental detector equipment is needed. Two Broad Energy Germanium Detectors (BEGe) were recently built up at the Goethe University Frankfurt. The first measurement of the partial neutron capture cross sections for the reaction $^{181}$Ta(n,γ) has been performed by using the activation technique.

1. Astrophysics of $^{181}$Ta(n,γ)

About 50% of the heavy element abundances are synthesized during the slow neutron capture process (s-process). Stable nuclei capture neutrons until an unstable isotope is reached. Depending on the decay and the neutron capture rate of the radioactive isotope, either another neutron is captured or it decays to the next heavier element. Therefore, the knowledge of the neutron capture rate and the beta decay rate is important to study the conditions in the interior of stars during the nucleosynthesis of elements. Thermally pulsing asymptotic giant branch (TP-AGB) stars during the advanced He burning stage are the source for s abundances beyond mass number 90 [1]. Fig. 1 shows the s-process path for Tantalum. The stable isotope $^{181}$Ta captures a neutron and produces the β− unstable isotope $^{182}$Ta partially in the ground state and isomeric state. The isomeric state decays with a half-life of $t_{1/2} = 16$ min to the ground state, which itself decays with a half-life of $t_{1/2} = 115$ d to the stable isotope $^{182}$W.

The decay properties of isomers can have a significant impact on the depopulation channels of isotopes under stellar conditions. In sufficiently hot environments, the
The population of isomers can be altered via thermal excitation or deexcitation [2]. The $^{182}\text{Ta}$ $\beta^-$ decay rate changes under stellar conditions by a factor of 3 [3]. Measuring the partial neutron capture cross section of isomeric states is challenging. Time-of-flight experiments are not able to distinguish the capture into the isomeric state from the capture into the ground state. Therefore, an activation experiment was performed in order to measure the partial neutron capture cross sections of $^{181}\text{Ta}$.

2. Activation experiment

The measurement of Maxwellian-averaged cross sections at $k_B T = 25$ keV was performed using the activation technique for many of stable and unstable isotopes along the chart of nuclide. For this purpose, protons were accelerate at the van de Graaff accelerator. The protons with an energy of $E_P = 1912$ keV impinged on a lithium target which produced a quasi-stellar neutron spectrum at $k_B T = 25$ keV (Fig. 2). To measure the neutron capture cross section additionally at higher energies, the energy of the incident protons was also set up to $E_P = 2100$ keV.

Behind the Lithium target, the $^{181}\text{Ta}$ metallic foil sample was sandwiched by two gold foils. The gold acts as neutron monitor, since its neutron capture cross section is well known. The neutron fluence can be determined for the position of the sample by interpolation. Additionally, a neutron detector monitors the variations of the neutron flux. The sample stack was mounted directly behind the Lithium target for a full
coverage of the neutron cone.

3. New BEGe detector setup

The decay of the produced radioactive nuclei can be detected by their characteristic gamma rays. For this purpose, sensitive experimental equipment is needed. A setup consisting of two Broad Energy Germanium Detectors (BEGe) was recently built up at the Goethe University Frankfurt. BEGe detectors are used to detect gamma rays emitted by the radioactive sample with high efficiency over a broad energy range. The Carbon Epoxy window has a thickness of 0.6 mm and is placed 5.5 mm in front of the crystal. The two detectors consist of cylindrical Ge crystals with a diameter of 70 mm and a thickness of 31 mm. They are mounted head to head on a rail construction. The sample is placed in the middle of both detectors. In order to change the distance to the sample, the detectors can be moved synchronous on the rail system. In order to reduce the background, a shielding consisting out of lead and copper was built.

Using this setup, the time-dependence of the freshly produced activity can be observed that allows the additional disentanglement of the partial cross sections populating isomeric states or the ground state.

4. Analysis

The radioactive samples were characterized by using $\gamma$-spectroscopy with the new BEGe detector setup. A typical radioactive $^{182}$Ta spectra can be seen in Fig. 3. The produced activity is given by:

$$A = \lambda \left( \frac{C_\gamma}{\epsilon_\gamma I_\gamma f_m f_{dt}} \right),$$  

(1)
Figure 3. The detected spectrum for $^{182}$Ta for different measurement time $t_m$ and waiting time $t_w$. The whole spectrum is shown in a), a zoom into the low energy region in b) and a zoom into the high energy region in c).

where the decay constant is $\lambda = \ln 2/t_{1/2}$, $C_\gamma$ are the detected events, $\epsilon_\gamma$ the efficiency, $I_\gamma$ the $\gamma$-intensity of the emitted $\gamma$-line, $f_m = 1 - \exp (-\lambda t_m)$ the correction for the decay during the measurement and $f_{dt}$ is the correction for the deadtime of the detection system.

The neutron spectra produced with proton energies of $E_p = 1912$ keV and $E_p = 2100$ keV are shown in Fig. 4. The Lithium layer had a thickness of 12 $\mu$m and was located 1 mm upstream of the $^{181}$Ta sample.
5. Discussion

The isomeric state of $^{182}$Ta was successfully resolved from the ground state. After detailed analysis, the partial neutron capture cross section of $^{181}$Ta will be determined. Using the new BEGe setup, it was possible to measure the activity of the samples with high efficiency. The incoming proton beam energy was varied up to $E_p = 2100$ keV. Additional measurements using different proton beam energies have to be performed and afterwards scaled to get the neutron capture cross section at $k_B T = 90$ keV [5].

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Reference

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