Extension of the activation method in nuclear astrophysics research

Final report

In this project the cross sections of several astrophysically relevant nuclear reactions were measured. Besides the astrophysical motivation the common feature of these experiments was the application of the activation method. In this report the results obtained on the roughly two dozen studied nuclear reactions will be shortly summarized.

The measurement of the typically very low cross sections is technically challenging. The activation method proved to be a powerful tool for such experiments. In the present project all the reactions were studied with activation. In many of the cases, however, the method had to be extended in different directions. The technical or methodological development required for such experiments will also be presented shortly at the given reactions.

The studied reactions fall into two main categories within the field of nuclear astrophysics: the heavy element nucleosynthesis, especially the astrophysical p-process and the hydrogen burning processes of stars. A short description of these are shortly reviewed before giving the details for the investigated reactions.

Heavy element nucleosynthesis, the astrophysical p-process

Chemical elements heavier than iron represent a special category in nuclear astrophysics as their synthesis do not contribute to the energy generation of stars. With some simplification, three main processes are responsible for the production of the heavy elements: the s-, r-, and p-processes. In this project, reactions relevant for the p-process were studied. The p-process is responsible for the synthesis of those proton-rich isotopes of the heavy element, which cannot be produced by neutron captures in the s-, and r-processes. The p-process is one of the least known processes of nucleosynthesis. The astrophysical site where the process takes place is still debated (most likely the p-isotopes are created in some of the layers of core collapse or type 1A supernovae). In addition, the nuclear reactions taking place in a p-process network are not known with the required accuracy. The high number of reactions involved in a p-process network necessitates the application of theoretically calculated cross sections which proved to be highly uncertain and unreliable. The experimental investigation of these reaction is therefore necessary to put the astrophysical calculation on a more robust ground.

The aim of our work was thus to measure the cross sections of reactions taking place in a p-process network. The measured cross sections are then compared with theoretical model calculations and conclusions are drawn from the comparison. Based on the measured data, modifications of some of the nuclear physics input parameters of the calculations are recommended which then lead to the better description of the data. With such modifications it is hoped that the model prediction can be improved also in the case of those reactions which cannot be studied experimentally but play an important role in the astrophysical process.

As it was observed in recent years, one of the most important and most uncertain nuclear physics input parameter of theoretical cross section calculations is the alpha-nucleus optical potential. The application of different optical potentials may lead to cross sections differing by more than one order of magnitude. This uncertainty of the predicted cross section may contribute to the poor modelling of the p-process. The study of the alpha-nucleus optical potential is therefore necessary and this was one of the most important focus points of our investigations.

The following list shows the p-process related reactions studied in this project with the results obtained and – if relevant - the technical developments related to the extension of the activation method. For all the measurements the cyclotron accelerator of Atomki was used with the exception of the first reaction which was studied at the Van de Graaff accelerator of Atomki.

- **^{92}Mo(p,γ)^{93}Tc** For this reaction contradicting results can be found in the literature. In our work, the reaction cross section was determined from the activation measurement of the thick target yield. Thick target yield measurement was never used before in relation to a p-process reaction. Our obtained results confirm that owing probably to the low level density of the residual nucleus the excitation function shows strong fluctuations and therefore the applicability of the statistical model is limited. From the measured yield data astrophysical reaction rates were directly derived which can be used in p-process network calculations. These rates are a factor of two lower than the previously recommended rates. [Gy. Gyürky *et al.*, Nucl. Phys. A **922,** (2014) 122.]
- **^{162}Er(α,γ)^{166}Yb and ^{162}Er(α,n)^{165}Yb** These reactions (and all the other p-process related reactions listed below) were never studied experimentally before in the relevant low energy range, thus our studies represent the first experimental results. The cross section of these reactions on ^{162}Er was measured using and improving the X-ray detection-based activation recently developed by our group. The fact that the ^{162}Er(α,γ)^{166}Yb cross section was measured below the (α,n) threshold for the first time in this mass region opens the opportunity to study directly the α-widths required for the determination of astrophysical reaction rates. The data clearly show that compound nucleus formation in this reaction proceeds differently than previously predicted. [G.G. Kiss *et al.,* Phys. Lett. B **735,** (2014) 40.]
- **^{64}Zn(p,α)^{61}Cu and ^{64}Zn(p,γ)^{65}Ga** By studying a (p,α) reaction with activation it was possible for the first time to investigate the alpha-nucleus optical potential in a reaction where the alpha particle is in the exit channel. This way the potential could be studied directly at the astrophysically important energy range. Therefore, our results prove for the first time directly in the astrophysical energy range that the standard optical potential used in reaction rate predictions for astrophysical network calculations fail to reproduce the experimental data and modifications are required. This is indicated in Fig. 1 where our measured data are compared with theoretical calculations and it can be seen that a modification is required in the optical potential in order to describe well the measured data. [Gy. Gyürky *et al.* Phys. Rev. C Rapid Communications **90**, (2014) 052801(R).]

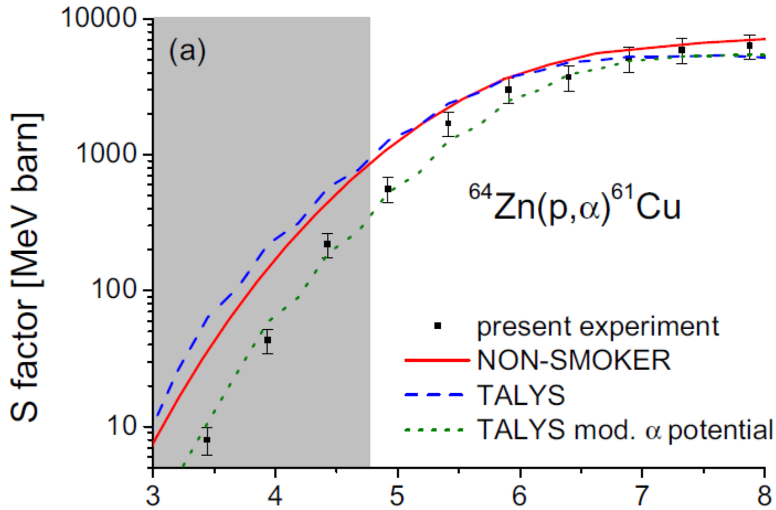

Fig. 1. Measured astrophysical S-factor of the $^{64}Zn(p,\alpha)^{61}Cu$ reaction compared with model calculations carried out with two different statistical model codes (TALYS and NON-SMOKER). The experimental data can be well described using a modified α+nucleus optical potential. The grey shaded area shows the astrophysically important energy range

- **$^{164}Er(\alpha,n)^{167}Yb$ and $^{166}Er(\alpha,n)^{169}Yb$** As a continuation of the study of alpha induced reaction on Er isotopes, two further (α,n) cross sections were measured with activation. The comparison of the results with model calculations shows that using the same optical potential for the α-width which was derived from combined $^{162}Er(\alpha,\gamma)^{166}Yb$ and $^{162}Er(\alpha,n)^{165}Yb$ measurement makes it plausible that a low-energy modification of the optical α+nucleus potential is needed. [G.G. Kiss *et al.,* J. Phys. G **42,** (2015) 055103.]
- **$^{107}Ag(\alpha,\gamma)^{111}In$ and $^{107}Ag(\alpha,\gamma)^{110}In$** The measured cross sections were found to be lower than theoretical predictions for the (α,γ) reaction channel. Varying the calculated averaged widths in the statistical model it became evident that the data for the (α,γ) and (α,n) reactions can only be simultaneously reproduced when rescaling the ratio of γ and neutron widths and using an energy-dependent imaginary part in the optical α + ^{107}Ag potential.
- **$^{152}Gd(p,\gamma)^{153}Tb$ and $^{152}Gd(p,\gamma)^{153}Tb$** These proton induced reactions were studied in order to investigate the recently suggested modification of the low energy proton-nucleus optical potential. This modification is confirmed for these isotopes as the calculations with the modified potential reproduce well the measured data. [R.T. Güray *et al.*, Phys. Rev. C **91**, (2015) 055809.]
- **$^{124}Xe(\alpha,\gamma)^{128}Ba$ and $^{124}Xe(\alpha,n)^{127}Ba$** For the measurement of these reactions on a rare noble gas isotope, a special thin window gas cell had to be developed and optimized for activation experiment. The $^{124}Xe(\alpha,\gamma)^{128}Ba$ reaction was given high priority in various p-process model calculation for experimental investigations. Our results included in supernova models indicate that the $^{128}Ba(\gamma,\alpha)^{124}Xe$ reaction path cannot be responsible for the observed ^{124}Xe abundance. [Z. Halász *et al.*, Phys. Rev. C **94,** (2016) 045801.]
- **$^{115}In(\alpha,\gamma)^{119}Sb$ and $^{115}In(\alpha,n)^{118}Sb$** For the determination of these cross sections the combined detection of γ-rays and X-rays following the decay of the reaction products was used. The simultaneous measurement of the (α,γ) and (α,n) cross sections allowed us to determine a best-fit combination of all parameters for the statistical model. It was found that the recently

developed ATOMKI-V1 potential gives the best description of the data. [G.G. Kiss *et al.,* Phys. Rev. C **97,** (2018) 055803.]

- **$^{121}Sb(\alpha,\gamma)^{125}I$, $^{121}Sb(\alpha,n)^{124}I$ and $^{123}Sb(\alpha,n)^{126}I$** Somewhat contrary to the findings in this mas region, the (α,n) data show that the α widths are predicted well for these reactions. The (α,γ) results are overestimated by the calculations which may be attributed to the applied neutron and γ widths. [Z. Korkulu *et al.,* Phys. Rev. C **97,** (2018) 045803.]
- **$^{191}Ir(\alpha,\gamma)^{195}Au$, $^{191}Ir(\alpha,n)^{195}Au$ and $^{193}Ir(\alpha,n)^{195}Au$** These reactions were studied for the first time by combining the thick target yield measurement with X-ray detection-based activation. These Ir isotopes are the heaviest nuclei where p-process related charged particle capture reactions were ever studied. The recently suggested energy-dependent modification of the α+nucleus optical potential is confirmed also for these heavy nuclei. [T. Szücs *et al.,* Phys. Lett. B **776,** (2018) 396.]

Hydrogen burning processes

Hydrogen burning is perhaps the most important source of energy that powers stars. Hydrogen burning can proceed though different processes. Besides the pp-chain that is the main process in low mass stars like our Sun, the different CNO cycles are important as they do not only provide energy for more massive stars, but contribute substantially to the synthesis of several chemical elements.

In the various CNO cycles many nuclear reactions are involved. The knowledge of these reactions is crucial for the better understanding of the operation of these cycles. These reactions were typically studied several times in the past. The high precision astrophysics of the 21th century requires, however, that the accuracy of the reaction cross sections increases significantly which necessitates further measurement and novel approaches.

In the framework of the present project two reactions of the CNO cycles were studied: $^{17}O(p,\gamma)^{18}F$ and $^{14}N(p,\gamma)^{15}O$. Both were studied with the activation method. Since the reaction products do not emit any γ-radiation during their decay, a special technique was used. The annihilation radiation following the positron decay of the produced isotopes was detected. This activation method was never, or rarely applied in the case of these reactions. The cross sections were measured in wide energy ranges which provide an important basis for the theoretical extrapolation to low, astrophysical energies. In the following some details and the results on these two reactions are shortly summarized.

- **$^{17}O(p,\gamma)^{18}F$** This reaction occurs in advanced CNO cycles where it competes with the $^{17}O(p,\alpha)^{14}N$ reaction. Its rate determines the branching ratio between the two reactions and it is strongly related to e.g. the calculated abundance of fluorine which can then be compared with observations. In a wide energy range only limited and contradicting data sets were available for this reaction. We carried out cross section measurement between 0.5 and 1.8 MeV proton energies. The low energy part of our data can be seen in Fig. 2. As the activation method provides directly the astrophysically important total reaction cross section, our results can be used to constrain theoretical calculations which are used to extrapolate the cross section to astrophysical energies. Our results are compared with existing data and an r-matrix analysis was also carried out in order to provide parameters for further comparison and astrophysical calculations. This experiment was the first completed scientific project on the new Tandetron accelerator of Atomki [Gy. Gyürky *et al.* Phys. Rev. C **95**, (2017) 035805.]

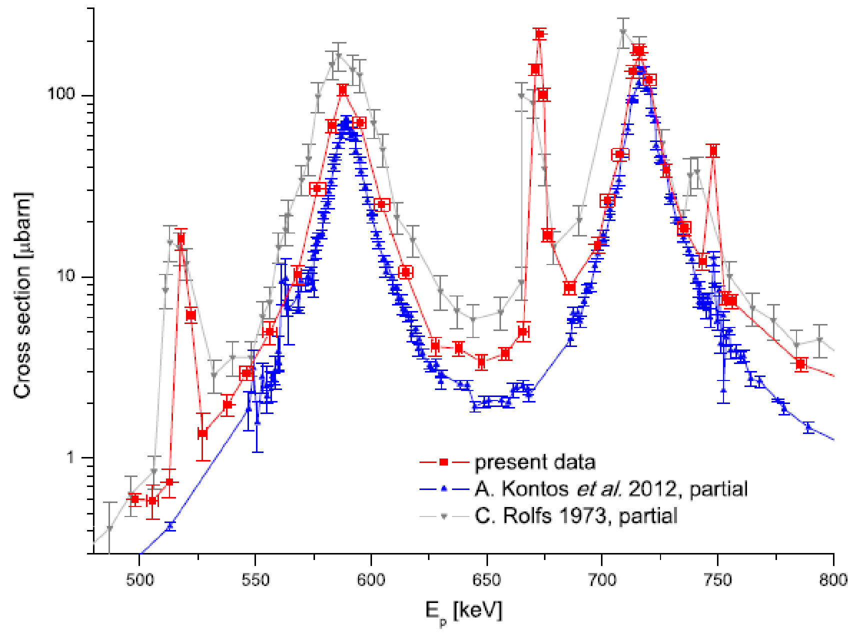

Fig. 2. Cross section of the $^{17}O(p,\gamma)^{18}F$ reaction measured in the present work and compared with literature data.

- **$^{14}N(p,\gamma)^{15}O$** This reaction is the slowest and therefore most important reaction of the first CNO cycle. Its rate determines the contribution of the CNO cycle to the energy generation of stars at various stages of stellar evolution. The knowledge of its cross section is thus necessary for various astrophysical problems from the age determination of globular clusters to the solar composition problem, etc. Owing to the short (about 2 minutes) half-life of the reaction product, the activation method was never used in the case of this reaction to obtain precise cross sections. We have developed a cyclic activation method for the determination of the cross section in the case of such a short half-life. In order to increase the precision and reliability of the results, extensive target characterization measurements were carried out. The results of these measurement and some feasibility studies have been published in conference proceedings. The measurement as well as the data analysis for the strength determination of two strong and important resonances are finished. The publication of these results is in progress. Further measurements for the direct capture component of the cross section in a wide energy range is in progress. [Gy. Gyürky *et al.* JPS Conf. Proc. **14**, (2017) 020403., Gy. Gyürky *et al.* EPJ Web of Conferences **165**, (2017) 01027., Gy. Gyürky *et al.,* in preparation]
- **Tandetron calibration** Both the $^{17}O(p,\gamma)^{18}F$ and $^{14}N(p,\gamma)^{15}O$ experiments were carried out using the new Tandetron accelerator of Atomki. In the case of a new accelerator, the precise energy calibration is crucial for the reliable knowledge of the absolute beam energies. Extensive calibration measurements were therefore carried out using resonant nuclear reactions as well as neutron threshold reactions. Based on these measurements the beam energies are known with better than 0.1 keV precision which is necessary for the astrophysical reaction rate determinations. [I. Rajta *et al.*, Nucl. Instr. Meth. A **880** (2018) 125.]

In summary, the activation method was used and extended in different directions for the measurement of astrophysical important nuclear reactions. In the fields of the p-process nucleosynthesis and stellar hydrogen burning, many reaction cross sections were measured either for the first time or with increased precision or with complementary methods. Our results contribute to the better understanding of these astrophysical processes. As the activation method played the central role in the experiments, an invited review paper about the activation technique in nuclear astrophysics has been written and submitted for publication. [Gy. Gyürky *et al.*, Eur. Phys. J. A *submitted*]