# Proton induced reactions and the astrophysical $p$ process

Ph.D. thesis

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## Introduction

Nuclei heavier than Iron are synthesized mainly via neutron capture in the $s$ (slow) and $r$ (rapid) processes. In both processes the neutron capture is followed by a $\beta$-decay, however, the neutron flux of the $r$ process is orders of magnitude higher. On the chart of isotopes, the path of the $s$ process follows the valley of stability, while the $r$ process takes place close to the neutron drip line. In addition, there are 35 heavy, relatively proton-rich nuclei, the so-called $p$ nuclei, which cannot be produced by neutron-capture because the path of the $s$ and $r$ processes is blocked by stable isobars. It is generally accepted that the process synthesizing these nuclei — the so called $p$-process — mainly involves a series of ($\gamma$,n) reactions starting from $s$ and $r$ seed nuclei and driving the material toward the neutron deficient region. Along this isotopic path, the binding energy of the neutrons becomes gradually larger and at some point ($\gamma$,$\alpha$) or ($\gamma$,p) reactions are taking place. The former one is more important in the case of the heavy and the latter one for light $p$ nuclei. Furthermore it was shown recently that (p,n) reactions — such as the $^{76}$Ge(p,n)$^{76}$As and $^{85}$Rb(p,n)$^{85}$Sr — on $s$ and $r$ seed nuclei can play important role too in the synthesis of the light $p$ nuclei. In addition, other subprocesses — like $rp$ and $\nu p$ processes — can give also contribution to the observed abundance of the $p$ nuclei.

High-energy photons with sufficient energy and intensity for photodisintegration are available only in explosive scenarios. The generally accepted models locate the $p$ process in the deep O/Ne-rich layers of massive stars either in the pre-supernova phase or in the supernova explosion where temperatures of a few times $10^9$ K are reached.

The modeling of the $p$ process nucleosynthesis requires a large network of nearly 20 000 nuclear reactions involving approximately 2000 stable as well as unstable nuclei. On one hand detailed information on the stellar environment (temperature, isotopic composition — $s$ and $r$ seed nuclei abundances — burning time, etc.) and on the other hand nuclear physics inputs (reaction rate, half life, mass, etc.) are required. All the reaction rates used in the model calculations including the dominant $\gamma$-induced reactions are generally calculated within the Hauser-Feshbach statistical model. Since the measurement of the cross section of the $\gamma$-induced reactions with the presently available technique is difficult or impossible, the rates of $\gamma$-induced reactions are based on theoretical calculations or — if experimental cross section data are available — can be derived from the inverse capture reactions using the detailed balance theorem. While there are compilations for the (n,$\gamma$) cross sections, very few charged-particle-induced reactions above the Iron region have been investigated experimentally, leaving the statistical model calculations largely untested. In recent years several cross section measurements have been carried out, however, the existing database is still not sufficient to check the reliability of the model calculations globally, therefore further experimental data are highly needed.

The aim of my Ph. D. work was to contribute to a more reliable reaction network calculation with providing measured proton-induced reaction rates to improve the reliability of the statistical model calculations. Furthermore with the study of the impact of nuclear inputs used for the reaction rate calculations we were able to give a better theoretical description of the existing experimental database with improving the proton optical potential applied in model calculations. We proved also that despite the negative $Q$ value it is possible to derive astrophysical reaction rates directly from the measured (p,n) cross section for both the (n,p) and (p,n) reaction. Consequently, proton- and alpha-induced reactions with negative $Q$ value can be and have to be studied experimentally.

## New scientific results

1. The cross sections of $^{70}$Ge(p,$\gamma$)$^{71}$As and $^{76}$Ge(p,n)$^{76}$As have been measured with high precision in the energy range relevant for the astrophysical $p$ process. The targets were produced with evaporating natural Germanium onto thin Aluminum foils. The number of target atoms were derived by weighing. The energy of the proton beam provided by the Van de Graaff and cyclotron accelerators of ATOMKI was between 1.6 and 4.4 MeV, covered in 400 keV steps. The induced $\gamma$-radiation of the product nuclei was detected by a HPGe detec-

tor, calibrated using standard radioactive sources. The derived cross sections have been compared to statistical model calculations using standard proton optical potential as input and a difference between the slope of the measured values and the theoretical predictions was found. This indicates that more detailed investigation of the input parameters of the statistical model calculations is necessary [R1, R2, T1].

2. The theoretical (p,$\gamma$) and (p,n) cross sections exhibit different dependences on nuclear inputs. In order to investigate the behavior of the cross section calculations as the function of these inputs a sensitivity test was carried out. The averaged widths of proton-, neutron-, and $\gamma$ channels used for the statistical model calculations have been varied systematically and independently by a factor of two up and down. For the (p,$\gamma$) reaction it was found that the cross section is mostly sensitive to the proton-widths at lower energies and above 2.5 MeV the sensitivity to the $\gamma$-widths become comparable or larger. It was found that the (p,n) reaction is dominantly sensitive to the variation of the proton-width except for an energy range of up to about 100 keV above the neutron threshold where the neutron-widths are still small. In summary, these calculations showed that the proton-widths are described well at lower energies while the $\gamma$-widths at higher energies. For completeness also the impact of variation of the level density was studied. In both reactions, this variation of the nuclear level density does not have any impact because transitions to the lowest levels are dominant [R2, T1].

3. The proton-widths used in the statistical model calculations are computed from the optical potential. Therefore the possibility of improving the proton potential was investigated. It was found that the best agreement between the $^{70}$Ge(p,$\gamma$)$^{71}$As and $^{76}$Ge(p,n)$^{76}$As experimental data and the theoretical calculations can be found with keeping the strength of the real part unchanged but, increasing the imaginary strength of the standard potential with about 70%. The cross section

calculations for the previously measured (p,$\gamma$) and (p,n) reactions in this mass and energy range were performed using the modified potential and a better agreement between the experimental data and the theoretical calculations was found [R2, T2].

4. Recent theoretical investigations showed that the $^{85}$Rb(p,n)$^{85}$Sr reaction plays particularly important role in $p$ process model calculations. For this reason, the cross section was derived at ATOMKI by measuring the yield of the emitted $\gamma$-radiation following the decay of the reaction product. The number of target atoms were derived using Rutherford Backscattering Spectroscopy too. Using this method it was also proved that the evaporated layer is homogeneous and the Rb to Cl ratio is constant. The energy range of the proton beam provided by the Van de Graaff and cyclotron accelerators was between 2.2 - 4.0 MeV — covered with 200 keV steps — since we wanted to investigate sensitively the region where the theoretical predictions are different for using the standard and the modified optical potential. The measured cross sections have been compared to statistical model calculations using standard inputs and the improved potential and in the latter case better agreement was found [R3, T2].

5. In stellar environments excited states are thermally populated whereas only reactions in the ground state of the target can be investigated in the laboratory. The influence of the excited target states is given by the so-called stellar enhancement factor, defined by the ratio of the stellar rate and the ground state rate. This factor considering a reaction with negative $Q$ value is usually much larger than for its inverse reaction with positive $Q$ value because in the latter case more excited states can be populated. Therefore, more astrophysically relevant transitions are neglected when experimentally studying a reaction with negative $Q$ value. In this work it was proved that despite the negative $Q$ value it is possible to derive astrophysical reaction rates for both the (n,p) and (p,n) reactions from the measured (p,n) data, as a consequence of the Coulomb suppression of the stellar en-

hancement factor. Similar argument can be applied for reactions with low and negative $Q$ value. Therefore certain $\alpha$-induced reactions for the $p$ process can be and have to be studied [R3, T2].

6. The proton capture cross sections of the two most proton-rich, stable isotopes of Cadmium have been measured for the first time in the energy range relevant to the astrophysical $p$ process ($E_p$ = 2.4 - 4.7 MeV). Highly enriched as well as natural Cd was evaporated onto thin Al foils and irradiated with proton beams from both the Van de Graaff and cyclotron accelerators of the ATOMKI. The cross sections were derived by measuring the $\gamma$-radiation following the $\beta$-decay of the $^{107,109}$In reaction products. The experimental results were compared with the predictions of Hauser-Feshbach statistical model calculations using standard nuclear inputs as well as our modified proton potential. In the latter case the calculation agrees better with the experimental results. The sensitivity of the model calculations to the proton- and $\gamma$-strengths was also examined [R4, R5, T1].

In summary, several cross sections of proton-induced reactions relevant for the astrophysical $p$ process have been measured at the relevant energies using the activation method. In all cases the results have been compared to statistical model calculations. The sensitivity of the theoretical calculations to the variation of the nuclear input parameters have been investigated. The proton optical potential has been improved to reach better agreement between the theoretical description and the experimental data. It also has been shown, that nuclear reactions with negative $Q$ value can be and have to be studied experimentally for the $p$ process network calculations.

# Publications

## Refereed journals

R1 **G. G. Kiss**, Gy. Gyürky, Z. Elekes, Zs. Fülöp, E. Somorjai, T. Rauscher, M. Wiescher,
*Investigation of proton-induced reactions on Germanium isotopes*,
Journal of Physics G. **35**, 4032 (2008).

R2 **G. G. Kiss**, Gy. Gyürky, Z. Elekes, Zs. Fülöp, E. Somorjai, T. Rauscher, M. Wiescher,
*$^{70}$Ge(p,$\gamma$)$^{71}$As and $^{76}$Ge(p,n)$^{76}$As cross sections for the astrophysical p process: Sensitivity of the optical proton potential at low energies*,
Physical Review C **76**, 505807 (2007).

R3 **G. G. Kiss**, Gy. Gyürky, A. Simon, Zs. Fülöp, E. Somorjai and T. Rauscher,
*Coulomb suppression of the stellar enhancement factor*,
accepted for publication Physical Review Letters (2008).

R4 Gy. Gyürky, **G. G. Kiss**, Z. Elekes, Zs. Fülöp, E. Somorjai,
*$^{106,108}$Cd(p,$\gamma$)$^{107,109}$In cross sections for the astrophysical p process*,
European Physical Journal A **27**, 141 (2006).

R5 Gy. Gyürky, **G. G. Kiss**, Z. Elekes, Zs. Fülöp, E. Somorjai, T. Rauscher,
*Proton capture cross section of $^{106,108}$Cd for the astrophysical p-process*,
Journal of Physics G **34**, 817 (2007).

**Conference Talks**

T1 **G. G. Kiss**, Gy. Gyürky, Zs. Fülöp, Z. Elekes, E. Somorjai, T. Rauscher and M. Wiescher,
*Investigation of proton capture reaction cross sections on light p nuclei*,
Nuclear Physics in Astrophysics III.,
Dresden, Germany, 26 - 31 March 2007.

T2 **G. G. Kiss**, Gy. Gyürky, A. Simon, Zs. Fülöp, E. Somorjai, T. Rauscher,
*Investigation of proton-induced reactions for the astrophysical p process*,
Capture Gamma Ray and Related Topics XIII.,
Cologne, Germany, 25 - 29 August 2008.