Introduction and scientific goals of the research

On the proton-rich side of the valley of stability there are about 30-35 nuclei (depending on state-of-art s and r process models) which are separated from the path of the s and r neutron capture processes. These mostly even-even isotopes between ^{74}Se and ^{196}Hg are the so-called *p*-nuclei. It is generally accepted that the main stellar mechanism synthesizing the *p*-nuclei – the so-called γ process – involves mainly photodisintegrations, dominantly (γ,n) reactions on preexisting more neutron-rich *s* and *r* seed nuclei. The high energy photons – necessary for the γ-induced reactions – are available in explosive nucleosynthetic scenarios like the Ne/O burning layer in type II supernovae where temperatures around a few GK are reached. Consecutive (γ,n) reactions drive the material towards the proton rich side of the valley of stability. As the neutron separation energy increases along this path, (γ,p) and (γ,α) reactions become stronger and process the material towards lighter elements, creating the so called γ process flow. Theoretical investigations agree on the fact that (γ,p) reactions are more important for the lighter *p*-nuclei while (γ,α) reactions are mainly important at higher masses.

Modelling the synthesis of the *p*-nuclei and calculating their abundances require an extended reaction network calculation involving more than 10^4 reactions on about 2000 mostly unstable nuclei. The reaction rates are calculated by using the Hauser-Feshbach statistical model, which relies on global alpha - nucleus optical potential parameter sets.

Despite the tremendous experimental and theoretical efforts of recent years, the synthesis of the *p*-nuclei is still one of the least known processes of nucleosynthesis, even the most recent model calculations are unable to reproduce well the Solar System abundances of the *p*-isotopes. This concerns the ambiguities in the astrophysical conditions under which the process takes place (*s* and *r* seed isotope abundances, peak temperatures, time scale, etc). However, large uncertainties are introduced into the calculations by the nuclear physics input, most importantly by the reaction rates – which are determined from cross sections. Therefore, the aim of the present grant was to provide high precision, experimentally determined nuclear physics inputs. During the grant I focused on solving three special problems:

1. In order to have a reaction network study based on solid ground, the experimental check of the statistical model predicted cross section is essential. Due to physical and technical reasons, the rates of the (γ,p) and/or (γ,α) photodisintegration reactions are typically obtained from the inverse capture cross sections. Before the start of the present grant – except the ^{169}Tm+α and ^{144}Sm+α reaction cross section measurements performed at Atomki using a novel approach – no experimental cross section data were available in the region of the heavy p nuclei at energies below the Coulomb barrier.
2. The alpha particle transmission coefficients used in the Hauser-Feshbach model are calculated from solving the Schrödinger equation with an optical potential, taken from global alpha-nucleus optical potential sets. Unfortunately, high precision alpha-scattering data at energies below the Coulomb barrier in the relevant mass range are scarce. Furthermore, before the start of the grant, scattering angular distribution data almost exclusively only on even-even nuclei were available.
3. To perform a reliable γ process network calculation the s and r seed nuclei abundances have to be known with high precision. The neutrons, necessary for

the s process are mostly released in the $^{13}C(\alpha,n)^{16}O$ reaction. Contrary to the extensive study of this reaction – due to the presence of a broad subthreshold resonance with unknown strength – its reaction rate was very uncertain.

Scientific achievements

I. Charged particle capture experiments

Alpha capture cross section measurements on heavy isotopes:

In the framework of the grant the $^{162}Er(\alpha,\gamma)$ [1], $^{162}Er(\alpha,n)$ [1], $^{164}Er(\alpha,n)$ [2], $^{166}Er(\alpha,n)$ [2], $^{168}Yb(\alpha,\gamma)$ [3], $^{168}Yb(\alpha,n)$ [3], $^{175}Lu(\alpha,\gamma)$, $^{176}Lu(\alpha,n)$ reactions were studied. The targets were made by vacuum evaporation of highly enriched material, onto thin Al backings. The fact that the thickness of the targets was derived using various ion beam analytical methods (Rutherford backscattering, Proton-induced x-ray emission, x-ray fluorescence spectroscopy) illustrates the synergy between the Nuclear Astrophysics group and the Ion Beam Analysis group of Atomki.

The irradiations were carried out using the cyclotron accelerator of Atomki and the cyclotron of PTB (*Physikalisch-Technische Bundesanstalt, Braunschweig, Németország*). The numbers of the reaction products were derived by measuring the gamma- and x-rays (the countings were carried out exclusively at Atomki using a Low Energy Photon Spectrometer (LEPS)) emitted by the radioactive reaction products.

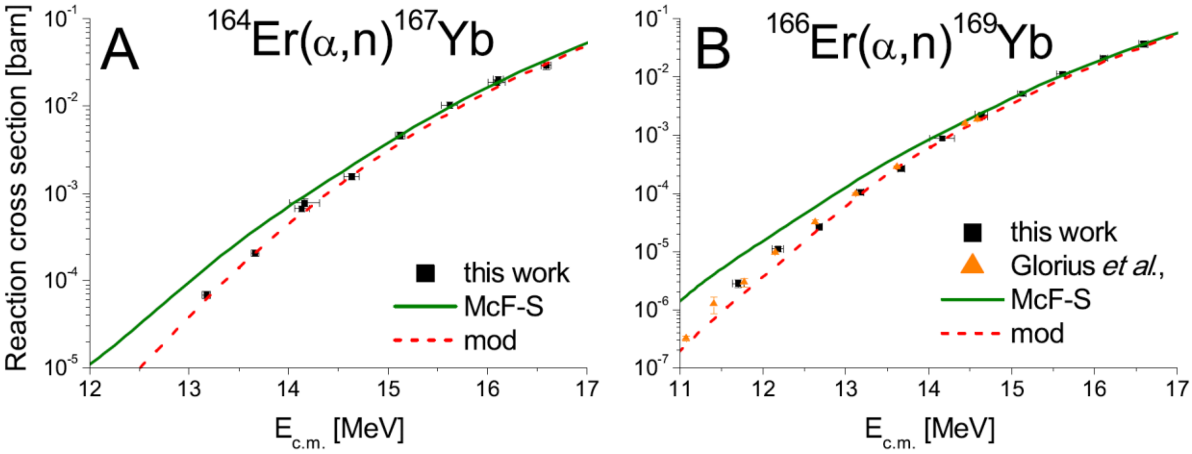

Figure 1. Experimental cross sections of the $^{164}Er(\alpha,n)$ and $^{166}Er(\alpha,n)$ reactions compared to statistical model calculations. It is obvious that the calculation performed using the modified alpha-nucleus optical potential parameterization describes the data significantly better than the original McF-S potential.

In the case of each cross section measurement the experimental data was compared to statistical model predictions. Furthermore, the sensitivity of the predicted cross sections on the ingredients of the H-F model was investigated.

The important break-through achieved in the framework of the grant was the simultaneous, high-precision measurement of the $^{162}Er(\alpha,\gamma)$ and $^{162}Er(\alpha,n)$ reaction cross sections in a wide energy range below the Coulomb barrier, which opened the opportunity to study directly the α-widths required for the determination of astrophysical reaction rates.

It was found to be crucial for the theoretical interpretation that the (α,γ) data were taken even below the (α,n) threshold. Thus, for the first time it was possible to show that the α+nucleus optical potential requires an energy-dependent Fermi-type modification consistently and unambiguously within the same measurement at high masses. This founding was cross checked by the measurement of (α,n) cross sections on other relatively proton-rich erbium isotopes. Figure 1 shows the experimental data compared to statistical model calculations performed using the standard and the modified alpha+nucleus optical potential. As can be seen – contrary to the calculation performed with the "standard" McF-S potential – the modified potential gives almost perfect description of the data.

The determination of the cross section of the ^{175}Lu(α,γ) and ^{176}Lu(α,n) is in progress. Several irradiations were already performed. In order to derive the reaction cross sections at each energy two irradiations had to be carried out using targets with different ^{175}Lu to ^{176}Lu ratio. Furthermore, the half-life of the produced ^{179}Ta nucleus is almost two years. Therefore – to reach sufficiently low statistical uncertainty – the length of the X-ray countings is typically about one month. The time needed for getting the cross sections exceeds more than a year and this way it is still in progress.

Proton-capture cross section measurements

In the framework of the grant the ^{92}Mo$(p,\gamma)^{93}$Tc [4], ^{92}Mo$(p,\gamma)^{93m}$Tc [4], ^{98}Mo$(p,\gamma)^{99m}$Tc [4], and the ^{130}Ba$(p,\gamma)^{131}$La [5], reaction cross sections were measured at Atomki and at the University of Cologne. The motivation for the first experiment was that previously strong fluctuations were observed in the ^{92}Mo$(p,\gamma)^{93}$Tc reaction cross section, which cannot be explained in the framework of the statistical model. Therefore, our aim was to repeat the cross section measurement. However, instead of the activation technique – used frequently by our group – for the first time the cross sections were derived from thick-target yield. This is an important local technical improvement since it opens the opportunity to study in the future nuclear reactions on isotopes with very high melting point (e.g. the ^{191}Ir+α reaction) when the vacuum evaporation isn't suitable technique for target production. While ~~the~~ our ^{92}Mo$(p,\gamma)^{93m}$Tc cross sections are in good agreement with the data taken from the literature, the ^{92}Mo$(p,\gamma)^{93}$Tc ground state cross sections are lower and are in better agreement with a recent measurement performed by the Cologne-group.

The cross section of the ^{130}Ba$(p,\gamma)^{131}$La reaction was studied in a new collaboration established with the University of Cologne. The targets were produced at Atomki and their thicknesses were derived using the PIXE technique. The irradiations and the counting of the emitted gamma rays were performed at Cologne. We found that the stellar reaction rate is increased by about 70% compared to the widely used NON-SMOKER calculations.

II. Investigation of the alpha-nucleus optical potential

Elastic alpha scattering experiments

Recently elastic alpha scattering experiment on ^{113,115}In, ^{142,146,148}Nd nuclei was carried out. The targets were produced by the evaporation of highly (95+%) enriched material onto thin carbon backings. The experiments were carried out using the large scattering chamber mounted at the cyclotron accelerator of Atomki. In the case of each isotope complete (20°-175°) angular distributions were measured at several energies: 16,15 and 18,0 MeV for indium isotopes and 16,15, 18,0 and 20,0 for ~~the~~ neodymium isotopes.

At first the ^{113}In(α,α) experimental data were analyzed [6]. The experimental angular distributions are compared to theoretical predictions calculated using different global alpha-nucleus optical potential parameter sets. We found that none of the available parameter sets are able to describe the new data (this fact indicates that further angular distribution measurements are needed) and therefore a local alpha-nucleus optical potential was constructed. The available ^{113}In(α,γ/n) reaction cross section data were used to evaluate global parameterizations, too. With a minor modification on the gamma-width, the local potential was able to describe the reaction cross section.

The preparation of the manuscript discussing the ^{115}In(α,α) reaction is in progress. Figure 2 shows the measured angular distribution compared to predictions calculated with the available optical potential parameter sets.

The data analysis in the case of the ^{142,146,148}Nd(α,α) reaction is in progress.

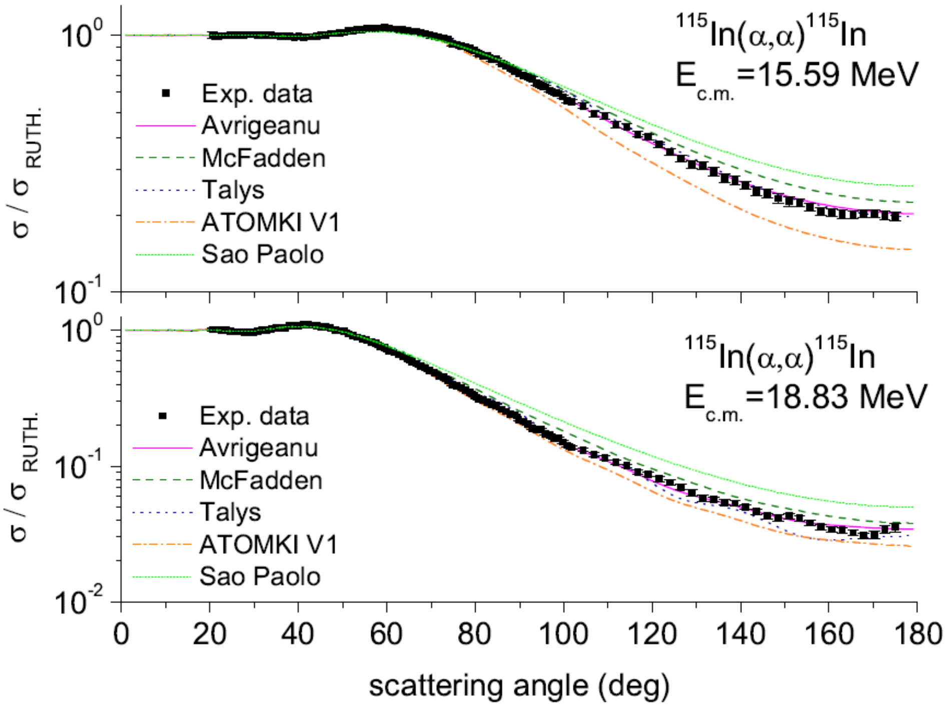

Figure 2. Rutherford normalized elastic scattering cross section of the ^{115}In(α,α)^{115}In reaction compared to predictions calculated using the available open-access global alpha-nucleus optical potential parameter sets.

Charged particle induced reactions on ^{64}Zn and the alpha-nucleus optical potential

In the framework of the present grant proton and alpha induced cross sections were measured on ^{64}Zn. As a result of the parallel measurement of the (α,γ), (α,n) and (α,p) cross sections [7], we confirmed for the first time experimentally that the total reaction cross section σ_{reac} of the α-induced reactions from the sum over all open reaction channels (measured by the activation technique) and σ_{reac} from the analysis of elastic scattering angular distributions are identical. This is an important experimental confirmation of the basic quantum-mechanical relation.

Usually, the cross section predictions of the statistical model are sensitive to different nuclear physics inputs. However, the sensitivity study in the case of the ^{64}Zn(p,α) reaction revealed that in the astrophysically relevant energy range in this special case the cross section calculation is only sensitive to the alpha width, computed from the alpha-nucleus optical potential. In turn, by the measurement of the (p,α) cross section we can directly study the alpha optical potential in the relevant energy region. The experiment was performed at Atomki, the data analysis finished and the manuscript discussing the results was accepted for publication at the Physical Review [8].

III. The investigation of the ^{13}C(α,n) reaction using Trojan Horse technique

The ^{13}C(α,n)^{16}O reaction is the neutron source for the main component of the s process, responsible for the production of most nuclei in the mass range $90 < A < 204$. It is active inside the helium-burning shell in asymptotic giant branch stars, at temperatures $T < 10^8$ K, corresponding to an energy interval where the ^{13}C(α,n)^{16}O is effective from 140 to 230 keV. In this region, the astrophysical S-factor is dominated by the -3 keV subthreshold resonance due to the 6.356 MeV level in ^{17}O, giving rise to a steep increase of the S-factor. Notwithstanding that it plays a crucial role in astrophysics, no direct measurements exist inside the s-process energy window. The magnitude of its contribution is still controversial as extrapolations (e.g. through the R matrix) and indirect techniques, such as the asymptotic normalization coefficient (ANC), yield inconsistent results.

The ^{13}C(α,n) reaction was studied through the ^{13}C(^{6}Li,n,^{16}O)d 3-body reaction performed in quasi-fee kinematics. The experiment was carried out at Florida State University. From the experimental results for the first time, the ANC for the 6.356 MeV level has been deduced through the Trojan Horse Method (THM) as well as the ~~n-~~partial n-width. Though about 22% larger ANC for the 6.356 MeV level was measured, the new THM experimental cross section agrees with the most recent extrapolation in the 140-230 keV energy interval. However, the uncertainty of the reaction rate was reduced to about 19% (for comparison: the accepted NACRE rate was +17% and -69%) [9].

Furthermore, we studied how does the new, precise reaction rate effecting the s process nucleosynthesis and by this the number of s seed nuclei. Using a post-process code (NEWTON) the abundance of heavy elements via slow neutron captures for stars less massive than 3 M_{Sun} and metallicity of $Z = 0.01$ were calculated. As a reference we choose the ^{86}Kr, ^{87}Rb, ^{96}Zr, and ^{142}Ce since they are located after an unstable isotope in the nuclear chart and the increase of the neutron density favours their production. We found that – compared to calculations performed with the NACRE value – the abundance of these isotopes are increased with about 30% [10].

Summary

In the framework of the PD104664 research grant **10 manuscripts** were published (or accepted for publication) with **total impact factor** of more than **40** (all manuscripts are available online at http://atomki.hu/~ggkiss and on arXiv). The results achieved were presented regularly on **international conferences** as **invited** (23rd Conference on Application of Accelerators in Research and Industry (2014, San Antonio, USA); 7th International Summer School on Nuclear Astrophysics (2013, Santa Tecla, Italy)) or **regular talks** (Capture Gamma Rays and Related Topics, CGS XV. (2014, Dresden, Germany); 4th International

Workshop on Compound Nuclear Reactions (2013, Maresias, Brazil) ; Nuclear Physics in Astrophysics VI (2013, Lisbon, Portugal)).

A **new collaboration was established** with the nuclear astrophysics group at **University of Cologne**, in the framework of this fruitful collaboration, the cross sections of the ^{168}Yb(α,γ/n) and ^{130}Ba(p,γ) reactions were measured during the two year long grant.

From the University of Debrecen three students (Nándor Sas in 2013, Ákos Tóth in 2014 and Tamás Tímár in 2014) participated in the experiments. Nándor Sas was responsible for the calibration of the LEPS detector. Ákos Tóth takes part in the analysis of the alpha-induced cross section measurements and Tamás Tímár is working on the elastic scattering data.

In the autumn of 2014 a **new experimental campaign** in **collaboration** with the **University of Valencia** was started at Atomki with a so-called **total absorption spectrometer** (TAS). Using this detector system online cross section measurement on several isotopes relevant for understanding the γ process becomes possible. With the permission of the President of the Council of Science and Engineering the cost of the transport, the installation (including the necessary workshop activity) and the extra cyclotron beamtime were partly covered from the budget of the PD104664 research grant.

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