High Precision Nuclear Astrophysics Experiments
Final Report
OTKA K120666

1. INTRODUCTION

The aim of the project was to perform nuclear physics experiments relevant to astrophysical phenomena. Recent developments from the wide range of astronomical observations like space telescopes, gravitational waves, neutrino detectors demand nuclear physics data where the reaction type, interaction energy range and accuracy of the data are set by astrophysics rather than standard nuclear physics. This requires a special approach from nuclear physics research, a combination of nuclear and astrophysics. This new interdisciplinary field called **nuclear astrophysics** by now has its own scientific strategy, technology demands, and worldwide research network. The nuclear astrophysics group of ATOMKI is well known in this scientific community, the low energy accelerators available in ATOMKI are playing key role in this field of research. This is shown by the fact that the recently awarded Horizon 2020 project (CHETEC-INFRA) includes ATOMKI as one of the experimental facilities where scientist from all over Europe can perform nuclear astrophysics oriented research with the help of the ATOMKI nuclear astrophysics group. See https://www.chetec-infra.eu/.

Below, a brief summary is given on the efforts and results of the project describing the three essential parts of a high precision nuclear astrophysics experiment: a) background conditions b) data collection and analysis c) astrophysical consequences.

2. ULTRA LOW BACKGROUND EXPERIMENTS

One of the key issues of low energy nuclear physics experiments is the extremely small cross section leading to the fact that the environmental background hampers the signature of the nuclear reaction. Since the present accelerator technology is limited by the beam intensity, the only solution is the understanding, reduction and control of the background. This ultra low background technology is also used in rare event detection experiments like neutrino detection or double beta decay studies. The natural suppression of the cosmic ray induced background is provided by deep underground laboratories.

The LUNA (Laboratory for Underground Astrophysics) collaboration is a group of Italian, Hungarian, British and German scientists running a low energy (400kV) particle accelerator underground. The location of the LUNA accelerator is the Gran Sasso National Laboratory in Italy where the cosmic muon background is suppressed by a factor of million and the cosmic ray dominant gamma ray background above 4MeV gamma energy is reduced by a factor of a thousand. From the experimental point of view the main task is to keep this background under control with a running accelerator where the particle beam can induce additional background.

Consequently, the essential part of an underground experiment is the analysis of the background conditions for the specific systems of beam, target and detectors. In many cases the background studies alone provide valuable scientific output so a standalone technology oriented publication precedes the nuclear data.

2.1. One of the major achievements of the present project provides insight to the **Big Bang Nucleosynthesis (BBN)** chain beginning with the formation of deuterium in the process p(n,γ)D. In order to understand the primordial abundance of deuterium, however, the D(p,γ) reaction should be known at BBN energies so a comparison can be made with the observations. With our experiments we could improve the baryon density estimation from BBN and independently verified the recent analysis of the cosmic microwave background. This result was published in the journal NATURE and raised considerable interest not only in the scientific community but for the general public, see for example:

- https://www.quantamagazine.org/physicists-pin-down-nuclear-reaction-from-moments-after-the-big-bang-20201111/
- https://www.vice.com/en/article/93wb97/scientists-recreated-nuclear-fusion-from-the-big-bang-under-a-mountain-in-italy

As it is indicated above the experiment also was preceded by a detailed study of the background conditions, where the commissioning was aimed at minimizing all sources of systematic uncertainty so we could reach a very low 3% systematic order enabling the improved prediction of BBN deuterium abundance.

2.2. While underground locations are essential to low background studies, in reality there are many **experimental problems should be solved at overground facilities** in order to get reliable results. The study of the $^{13}C(\alpha,n)^{16}O$ is a clear example for such a collaboration where the ATOMKI overground accelerators have been used together with the LUNA underground accelerator leading to high precision data.

One of the main neutron sources for the astrophysical s-process is the reaction $^{13}C(\alpha,n)^{16}O$, taking place in thermally pulsing asymptotic giant branch stars at temperatures around 90MK. To model the nucleosynthesis during this process the reaction cross section needs to be known in the 150–230 keV center-of-mass energy window. At these sub-Coulomb energies, direct measurements are severely affected by the low event rate, making us so far rely on input from indirect methods and extrapolations from higher-energy direct data. This leads to an uncertainty in the cross section at the relevant energies too high to reliably constrain the nuclear physics input to s-process calculations.

Our results from the deep-underground measurement covered the energy range 230–300keV, with drastically reduced uncertainties over previous measurements and for the first time providing data directly inside the s-process energy region. That allowed us to estimate the impact of our revised reaction rate on selected stellar models.

The ATOMKI team with the support of the present OTKA project played a crucial role in the experiment overground and underground.

- Direct measurements of reaction cross-sections at astrophysical energies often require the use of solid targets able to withstand high ion beam currents for extended periods of time. Thus, monitoring target thickness, isotopic composition, and target stoichiometry during data taking is critical to account for possible target modifications and to reduce uncertainties in the final cross-section results. We developed a new application of the shape analysis of primary γ rays emitted by the $^{13}C(p,\gamma)^{14}N$ radiative capture reaction. This approach was used to monitor ^{13}C target degradation in situ during the $^{13}C(\alpha,n)^{16}O$ data taking campaign. The method has been validated by experiments at ATOMKI using the Nuclear Resonant Reaction Analysis method.

- A new neutron detector array has been developed for the investigation of the reaction in the low-background environment. Eighteen ^{3}He counters are arranged in two different configurations (in a vertical and a horizontal orientation) to optimize neutron detection efficiency, target handling and target cooling over the investigated energy range. As a result we reached a total background rate of 1.23 ± 0.12 counts/hour, an improvement of two orders of magnitude over the state of the art. The absolute neutron detection efficiency of the setup was determined in ATOMKI using the $^{51}V(p,n)^{51}Cr$ reaction via the activation method and an AmBe radioactive source, and completed with a GEANT4 simulation.

2.3. **The importance of chemically and isotopically clean target production** is essential for low background experiments. This is demonstrated by our development of oxygen targets in the form of Ta_2O_5. The targets were prepared by anodisation of tantalum backings in enriched water (up to 66% in ^{17}O and up to 96% in ^{18}O). Special care was devoted to minimizing the presence of any contaminants that could induce unwanted background reactions with the beam in the energy region of astrophysical interest. That technical development made feasible to carry out several low energy experiments using oxigen targets.

- The $^{18}O(p,\alpha)^{15}N$ reaction affects the synthesis of ^{15}N, ^{18}O and ^{19}F isotopes, whose abundances can be used to probe the nucleosynthesis and mixing processes occurring deep inside asymptotic giant branch (AGB) stars. We performed a low-background direct measurement of the $^{18}O(p,\alpha)^{15}N$ reaction cross-section down to Ec.m.=55keV, the lowest energy measured to date corresponding to a cross-section of less than 1 picobarn/sr. The strength of a key resonance at center of mass energy Er=90keV was found to be a factor of 10 higher than previously reported. Over a wide temperature range, T=0.01–1.00GK, our new astrophysical rate is both more accurate and precise than recent evaluations.

- We performed a direct measurement of the $^{18}O(p,\gamma)^{19}F$ cross section using a high-efficiency 4πBGO summing detector underground. The reaction cross section has been directly determined for the first time from 140 keV down to 85 keV and the different cross section components have been obtained individually. The previously highly uncertain strength of the 90 keV resonance was found to be 0.53 ±0.07 neV, three orders of magnitude lower than an indirect estimate based on nuclear properties of the resonant state and a factor of 20 lower than a recently established upper limit, excluding the possibility that the 90 keV resonance can contribute significantly to the stellar reaction rate.

- The $^{17}O(p,\gamma)^{18}F$ reaction plays an important role in hydrogen burning processes in several different stages of stellar evolution. The rate of this reaction must therefore be known with high accuracy at the relevant temperatures in order to provide the necessary input for astrophysical models. The cross section is measured using the activation method. This method provides directly the total cross section which can be compared with model calculations. With this technique some typical systematic uncertainties encountered in in-beam γ -spectroscopy experiments can be avoided. The cross section was measured in ATOMKI between 500 keV and 1.8 MeV proton energies with a total uncertainty of typically 10%. Using an independent experimental technique, the literature cross section data of $^{17}O(p,\gamma)^{18}F$ is confirmed in the energy region of the resonances while a lower direct capture cross section is recommended at higher energies. Our dataset provides a constraint for the theoretical cross sections.

It is important to mention that the entire $^{17}O(p,\gamma)^{18}F$ experiment was carried out at the ATOMKI Tandetron accelerator using the activation method in which the ATOMKI team is a known expert. This is reflected by the fact that the European Physical Journal invited us for a review article on the activation method for cross section measurements in nuclear astrophysics.

2.4. **Studies of nuclear reactions involving the radioactive ^{7}Be nucleus**

In the Solar Standard Model (SSM) ^{7}Be is formed through the $^{3}He(\alpha,\gamma)^{7}Be$ reaction, and can be destroyed by radioactive decay or via the $^{7}Be(p,\gamma)^{8}B$ reaction. In particular, the $^{7}Be(p,\gamma)^{8}B$ reaction plays a key role as it affects the flux of ^{7}Be and ^{8}B solar neutrinos. Large systematic discrepancies exist on both the absolute value and the energy dependence of its cross section. The ATOMKI cyclotron accelerator can produce ^{7}Be isotopes. This production can be realized via the $^{7}Li(p,n)^{7}Be$ reaction using 11MeV protons, available at the ATOMKI cyclotron with high intensity. This isotope can be used as radioactive beam at the ERNA facility in Italy. Also the ATOMKI team has expertise in the low level detection of ^{7}Be and that can lead to sensitive experiments on $^{3}He(\alpha,\gamma)^{7}Be$ using the above mentioned activation method.

- A direct measurement of $^{7}Be(p,\gamma)^{8}B$ using a radioactive 7Be ion beam on a pure hydrogen gas target has been since long envisioned. Our results obtained using the intense ATOMKI provided ^{7}Be beam available at the Tandem Accelerator Laboratory coupled to the recoil mass separator ERNA in the energy range Ecm=367 to 812 keV.

Our results are compatible only with a part of previous measurements, in particular those indicating a low value of the astrophysical S-factor at zero energy S17, thus exacerbating the discrepancy between existing measurements. The analysis of our data together with the results of previous data provides an estimate S17(0)=20.0±0.8 eV·b, where systematic uncertainties are inflated to obtain a statistically compatible data set

- Recently, a previously unobserved resonance in the ^{6}Li(p,γ)^{7}Be reaction suggested a new level in ^{7}Be, which would also have an impact on the ^{3}He(α,γ)^{7}Be reaction in the energy range above 4.0 MeV. The aim of our experiment in ATOMKI was to measure the ^{3}He(α,γ)^{7}Be reaction cross section in the energy range of the proposed level. For this investigation again the activation technique was used. A thin window gas-cell target confining ^{3}He gas was irradiated using an α beam. The ^{7}Be produced was implanted into the exit foil. The ^{7}Be activity was determined by counting the γ rays following its decay by a well-shielded high-purity germanium detector. Reaction cross sections have been determined between Ecm = 4.0 and 4.4 MeV with 0.04-MeV steps covering the energy range of the proposed nuclear level. One lower-energy cross-section point Since a constant cross section of around 10.5 μb was observed around the ^{7}Be proton separation energy we could exclude the previously reported resonance.

- We performed also an underground measurement of the ^{6}Li(p,γ)^{7}Be cross section at the Laboratory for Underground Nuclear Astrophysics, covering the center-of-mass energy range E = 60–350 keV. Our independent results also rule out the existence of low-energy resonances in ^{6}Li(p,γ)^{7}Be. The astrophysical S-factor varies smoothly with energy, in agreement with theoretical models.

3. HEAVY ELEMENT NUCLEOSYNTHESIS

The first ATOMKI experiment on heavy element nucleosynthesis was published in 1997 and since than our nuclear astrophysics group started a very successful systematic study on proton and alpha induced nuclear reactions on heavy isotopes, mainly for the p-process. The key ingredients are the sophisticated target production, the applicable energy range of our particle accelerators, and our experience in the activation method. Also we identified the importance of optical alpha potentials as the most important input parameters for the statistical calculations. During the present project period we continued the p-process studies, but we also started experiments in ATOMKI aiming at the weak r-process, and started an experimental project on r-process at RIKEN, Japan using radioactive beams.

3.1. Astrophysical p-process

We carried out a large number of studies of alpha induced (α,γ) and (α,n) reactions, close to the p-process relevant Gamow window on heavy elements. In all cases the activation method was used. We extended the method from gamma ray detection to X-ray studies to improve our sensitivity and to reach so far unavailable reactions.

- ^{162}Er, ^{115}In, ^{197}Au, various Sb and Iridium isotopes were used as target materials for the reaction studies. In all cases comparison has been made to statistical model predictions using a large variety of input parameters.

- While the ^{64}Zn is not as heavy as the p-nuclei its study served as a test bench for the statistical model. Uncertainties of these calculations are related to ambiguities in the adjustment of the potential parameters to experimental elastic scattering angular distributions (typically at higher energies) and to the energy dependence of the effective α-nucleus potentials. Our work investigated cross sections of α-induced reactions for ^{64}Zn at low energies and their dependence on the chosen input parameters of the statistical model calculations. The new experimental data from the ATOMKI experiments allow for a $\chi 2$-based estimate of the uncertainties of calculated cross sections at very low energies. Recently measured data for the (α,γ), (α,n), and (α,p) reactions on ^{64}Zn are compared to calculations in the statistical model. The present experimental data for ^{64}Zn in combination with the statistical model calculations allowed us to constrain the astrophysical reaction rate within about a factor of 2.

- The standard calculations in the statistical model show a dramatic sensitivity to the chosen α-nucleus potential. Our new study in Physical Review Letters explained the reason for this dramatic sensitivity which results from the tail of the imaginary α-nucleus potential in the underlying optical model calculation of the total reaction cross section. As an alternative to the optical model, a simple barrier transmission model was suggested. It is shown that this simple model in combination with a well-chosen α-nucleus potential is able to predict total α-induced reaction cross sections for a wide range of heavy target nuclei above $A \gtrsim 150$ with uncertainties below a factor of 2. The new predictions from the simple model do not require any adjustment of parameters to experimental reaction cross sections whereas in previous statistical model calculations all predictions remained very uncertain because the parameters of the α-nucleus potential had to be adjusted to experimental data.

3.2. r- and weak r-processes

Lighter heavy elements beyond iron and up to around silver can form in neutrino-driven ejecta in core-collapse supernovae and neutron star mergers. Slightly neutron-rich conditions favor a weak r-process that follows a path close to stability. Therefore, the beta decays are slow compared to the expansion timescales, and (α,n) reactions become critical to move matter toward heavier nuclei. The rates of these reactions are calculated with the statistical model and their main uncertainty, at energies relevant for the weak r-process, is the α+nucleus optical potential. There are several sets of parameters to calculate the α+nucleus optical potential leading to large deviations for the reaction rates, exceeding even one order of magnitude.

- Recently the $^{96}Zr(\alpha,n)^{99}Mo$ reaction has been identified as a key reaction that impacts the production of elements from Ru to Cd. Using the ATOMKI accelerators, we presented the first cross section measurement of this reaction at energies relevant for the weak r-process. The new data provide a stringent test of various model predictions which is necessary to improve the precision of the weak r-process network calculations. The strongly reduced reaction rate uncertainty leads to very well-constrained nucleosynthesis yields for Z = 44–48 isotopes under different neutrino-driven wind conditions.

For neutron-rich nuclei far from stability, beta-delayed neutron emission is the dominant decay process. The probability for a nucleus to emit a delayed neutron (Pn) yields information on the beta-strength distribution and the level structure of the daughter nucleus. Most of the 3000 neutron-rich nuclei still predicted to exist are expected to be beta-delayed neutron emitters. In addition to the importance for nuclear structure, Pn values are among the most important input parameters for calculations of the synthesis of neutron-rich heavy elements by the astrophysical rapid neutron-capture process (r-process). Determining many yet unmeasured Pn values is critical for testing the conditions of the astrophysical environment, and to provide clues about the sites of the r-process. Consequently, the measurement of beta-delayed neutron emission probabilities provides unique information about the nuclear structure in exotic nuclei and contributes to the understanding of the formation of the heavy elements in the universe.

- As part of the BRIKEN collaboration in Japan we developed and commissioned an experimental setup aiming at beta delayed neutron studies in neutron rich nuclei produced by the RIKEN Radioactive Beam Factory.

4. SUMMARY

During the project period we published about 45 papers with the Impact Factor of about 200. Apart from the flagship NATURE publication we published 10 different letters, 3 of them in Physical Review Letters. Two of our papers became Editor’s Choice, and one of our team members received the outstanding referee status of Physical Review C.

In 2018 we organized in ATOMKI an international workshop entitled **Nuclear Physics in Stellar Explosions** discussing relevant topics as

- Evidences of explosive nucleosynthesis
- Nuclear Theory in Astrophysics (mass models, β-decay rates, optical potentials)
- Modeling of the nucleosynthesis processes (r-, rp-, and γ- process network calculations)
- Recent r-, rp-, and γ-process related experiments

The above topics of the workshop describes well the wide range activity of the ATOMKI nuclear astrophysics team. This activity is further supported in the future by the several Ph.D. students and international collaborators interested in our work.