Nucleosynthesis of proton-rich nuclei. Experimental results on the $rp$-process

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Abstract. We report in this study the nuclear properties of proton-rich isotopes located along the $rp$-process path. The experiments have recently been performed at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. The level properties above the proton separation energy of the nuclei $^{30}$S, $^{36}$K and $^{37}$Ca were measured with precision of $< 10$ keV. This will allow a reduction in the determination of the astrophysical $(p,\gamma)$ reaction rate under $rp$-process conditions.

1. Introduction
Over the past two decades, the study of extra-solar X-ray objects has entered a new era with the launching of precision X-ray observatories, XMM-Newton and Chandra X-ray observatory being the two latest examples operating since 1999. These and other observatories have provided and continue to produce data with a high degree of sensitivity and resolution, leading to
new discoveries such as super-bursts or ms-oscillations, and therefore challenging physicists to describe these novel phenomena. Among the observed objects, Type I X-ray bursts are characterized as thermonuclear explosions on the surface of accreting neutron stars in a binary system. After accumulation of hydrogen and helium from the envelope of the companion star on the surface of the neutron star, the burst is powered by the rapid proton capture process \((rp\)-process) \cite{1, 2}, which consist of a series of \((\alpha,p)\) and \((p,\gamma)\) reactions, and subsequent \(\beta^+\)-decays, creating proton-rich isotopes and releasing energy on the order of \(10^{40}\) ergs over a period between 10 and 100 seconds. For further details on X-ray sources, refer to the recent review of Schatz and Rehm \cite{3}.

Nuclear physics is a key input necessary to the modeling of the evolution of the burst. Nuclear masses, \(\beta\)-decay half lives, and \((\alpha,p)\) and \((p,\gamma)\) reaction rates determine quantities such as the time scale, light output and energy release in the burst, as well as the reaction path and the final abundance distribution of elements synthesized during the explosion. As for the determination of the \((p,\gamma)\) reaction rates, in most of the cases at masses \(A \leq 40\), the reaction is dominated by a resonant contribution from one or a few levels close to the particle threshold. A precise knowledge of the nuclear structure and masses is essential to provide the most accurate possible proton-capture reaction rates in this region of nuclei, whose reactions power the rise of the burst.

| \(E_x\) (keV) | \(J^\pi\) | \(E_x\) (keV) | \(J^\pi\) |
|-------------|---------|-------------|---------|
| 4020        | 3/2     | 4009.87 (8) | 9/2     |
| 3770        | 9/2     | 3741.22 (11)| 5/2     |
| 3710        | 3/2     | 3707.79 (9) | 3/2     |
| 3630        | 5/2     | 3626.82 (6) | 3/2     |
| 3500        | 5/2     | 3103.50 (2) | 7/2     |
| 3090        | 5/2     | 3086.14 (7) | 5/2     |
| 2683        | 7/2     | 1613 (17)   | 3/2     |
| 0.0         | 3/2     | 0.0         | 3/2     |

Figure 1. (Color online) Knowledge on the level scheme for the \(A = 37\) mirror nuclei \(^{37}\)Ca (left) and \(^{37}\)Cl (right) at the time the experiments were performed \cite{4}, represented by solid lines. The value of the proton separation energy in \(^{37}\)Ca \cite{5} recently measured is also shown. Only the first excited state in \(^{37}\)Ca had been previously measured \cite{6}. The dashed lines in the case of \(^{37}\)Ca are taken directly from the mirror states in \(^{37}\)Cl with a Coulomb shift estimated for the negative parity states from the fp-shell \cite{7}.

As an example, the present knowledge on the level scheme of the nucleus \(^{37}\)Ca is shown in figure 1. Those states located close to and above the proton separation energy will contribute significantly to the proton capture reaction rate at burst temperatures. Typical uncertainties from shell model calculations of the order of 100 keV could easily translate into orders of magnitude uncertainty in the proton capture reaction rate \cite{8}. A precise determination of the level structure of nuclei involved in the \(rp\)-process would reduce the uncertainty in the calculation of \((p,\gamma)\) reaction rates. In order to achieve this goal, several experiments have recently been performed at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University aiming to improve the knowledge of the level structure of proton-rich isotopes located along the \(rp\)-process path. The experimental procedure followed was similar to that applied to the study of the properties of the isotope \(^{33}\)Ar \cite{8}.

This contribution presents the status of the experimental results from measurements on the
isotopes $^{30}\text{S}$, $^{36}\text{K}$ and $^{37}\text{Ca}$ using a specific experimental technique at the NSCL. The detailed discussion of the results obtained will be the topic of upcoming publications [9, 10] and is outside the scope of this manuscript. The possible reduction of the uncertainties in the determination of the reaction rate and their implications in X-ray burst modeling are considered as well.

2. Experimental Procedure

The experiments were performed at the Coupled Cyclotron Facility (CCF) at the NSCL. Two different settings were chosen for the investigation of the nuclei of interest. For the case of $^{30}\text{S}$, a $^{36}\text{Ar}$ primary beam was accelerated up to 140 MeV/u and fragmented on a $^9\text{Be}$ target of 1151 mg/cm$^2$ thickness at the entrance of the A1900 fragment separator [11]. The secondary beam emerging from the A1900 consisted predominantly of $^{31}\text{S}$ (74.7 %), but also $^{32}\text{Cl}$ (11.6 %) and $^{30}\text{P}$ (12.6 %). The beam was guided towards the entrance of the vertical S800 spectrometer [12] with an energy of approximately 71 MeV/u, and further down to the target area of the S800. A polypropylene secondary target was used to accomplish the one neutron removal process on the $^{31}\text{S}$ secondary beam to obtain $^{30}\text{S}^*$. The photon-decay of the produced $^{30}\text{S}$ nuclei was detected by 17 detectors of the Segmented Germanium Array (SeGA) [13], distributed over two rings under 90 and 37 degrees respectively to the beam direction. The measured gamma rays were detected in coincidence with the recoil nuclei at the focal plane of the S800.

In the study of the level properties of $^{36}\text{K}$ and $^{37}\text{Ca}$, a primary beam of $^{40}\text{Ca}$ was accelerated to 140 MeV/u at the CCF. A secondary beam containing $^{38}\text{Ca}$ (61 %), $^{37}\text{K}$ (28 %), $^{36}\text{Ar}$ (10 %) and $^{40}\text{Cl}$ (1 %) was delivered to the S800 experimental area with a setup similar to that previously described. The photons from the decay of the produced $^{36}\text{K}$ and $^{37}\text{Ca}$ nuclei were again measured using the SeGA array, and detected in coincidence with the recoil nuclei at the S800 focal plane.

Several nuclear species were produced from the interaction of the secondary beams with the reaction target. The situation is partially shown in figure 2 for the particular cases of $^{31}\text{S}$ (left panel) and $^{35}\text{Ca}$ (right panel). Both figures show $N - Z$ in the abscissa, which has been derived from the time needed by the particles to travel from the beginning of the S800 spectrometer to its final focal plane. The ordinate axis gives $Z$, which roughly corresponds to the energy lost by the particles at an ionization chamber located at the S800 focal plane. The high energy loss and timing resolutions enabled an easy separation of the isotope of interest for further analysis.

3. Present status of the analysis

The photons emitted by the nuclei under study were measured by the detectors from the SeGA. The velocity of the beam was over 1/3 of the speed of light and thus the Doppler shift between the particle and the laboratory frame was significant. Details of the reconstruction analysis will be published elsewhere [9, 10]. The resulting spectra for the three nuclei under consideration in this work, $^{30}\text{S}$, $^{36}\text{K}$ and $^{37}\text{Ca}$ are displayed in figure 3.

All measured transitions in $^{37}\text{Ca}$, with the exception of the first excited state at 1.61 MeV, are signatures of states that have been detected for the first time, and they will be the topic of a dedicated paper [10]. Similarly, the improved precision of the measured levels in $^{30}\text{K}$ and its effect in the uncertainties determining the $^{35}\text{Ar}(p,\gamma)^{36}\text{K}$ reaction rate will be extensively discussed elsewhere [10]. The focus of this paper will be the motivation and preliminary results obtained for the the nucleus $^{30}\text{S}$.

Interest in $^{30}\text{S}$ has increased enormously in recent years as it is considered a possible waiting-point on the $np$-process [14, 15]. This statement is made on the $(p,\gamma)(\gamma,p)$ equilibrium between $^{30}\text{S}$ and $^{34}\text{Cl}$ [16], and remains under consideration based on the spectroscopic properties of $^{30}\text{S}$ and the rate of the $^{36}\text{S}(\alpha,p)$ reaction [17], which is a possible alternative to the proton capture.

The main source of uncertainty in the $^{29}\text{P}(p,\gamma)^{30}\text{S}$ reaction rate is the location of two resonances above the proton threshold ($S_p=4400$ (3) keV [18]), predicted by Iliadis et al. [19] at
Figure 2. (Color online) Particle identification plots. In both cases, the time-of-flight information on the X-axis has been transformed into $N-Z$, whereas the energy loss of the particles is expressed in $Z$ units along the Y-axis. The reaction products from the $^{31}\text{S}$ beam are shown in the left panel, while the right panel presents the nuclei observed from the reactions on the $^{38}\text{Ca}$ beam. The quality of the separation in both cases permitted a clear identification of the nuclei of interest for further analysis.

Figure 3. Doppler corrected photon spectrum measured in coincidence with recoil $^{30}\text{S}$ (upper left), $^{36}\text{K}$ (upper right) and $^{37}\text{Ca}$ (bottom). The most dominant transition in all cases corresponded to the decay from the first excited state in the studied nucleus.

$4733\ (3^+)$ and $4888\ (2^+)$ keV. Typical uncertainties in the determination of the energy levels of the order of 100 keV translate into an uncertainty of up to several orders of magnitude in the determination of the $^{29}\text{P}(p,\gamma)^{30}\text{S}$ reaction rate. The reaction rate for the considered reaction in the relevant temperature range for X-ray bursts is shown in figure 4. The rate derived using this spectroscopic information is given by the light-green area.

Several measurements performed over the years \cite{20, 21, 22, 23, 24} mapped the level structure of $^{30}\text{S}$ using different experimental techniques, from transfer reactions to beta-decay studies. None of these attempts detected the existence of the two mentioned levels just above the particle threshold. Only recently, Bardayan et al. \cite{25} presented the measurement of the $3^+$
state at an energy of 4704 (5) keV by means of the $^{32}\text{S}(p,t)^{30}\text{S}$ reaction. That measurement resulted in a reduction of the proton capture rate uncertainties at low temperatures, which is also the relevant temperature range for novae nucleosynthesis. The proton capture rate based on Bardayan’s result is shown by the red area in figure 4. At higher temperatures however, the contribution from the resonant capture via the $2^+$ state dominates the process and uncertainties increase again.

In our experiment we detected all known transitions up to 5.1 MeV using a single experimental approach. Additionally, we observed two novel gamma lines at energies that are identified as candidates of the de-excitation of the missing excited states close above the proton threshold. The analysis of the data is in a preliminary stage. Final results and details of the analysis will be presented in a dedicated manuscript [9].

4. Implications on X-ray burst modeling
The reaction rate for the $^{29}\text{P}(p,\gamma)^{30}\text{S}$ reaction calculated based on the preliminary spectroscopic information derived from our measurement is shown in figure 4 as the black curve. The uncertainties shown in the figure are exclusively due to the errors in the determination of the resonance energies. The preliminary reaction rate presented in this work shows an uncertainty of roughly a factor of 2 over the entire temperature range.

In order to estimate the impact of the new rate in the X-ray burst modeling, calculations using the one-dimensional multi-zone KEPLER model [26] are underway. Preliminary results show that the reduction of the uncertainties and the deduced rate for the $^{29}\text{P}(p,\gamma)^{30}\text{S}$ reaction do not have a remarkable impact on the evolution of the burst within this model.

The model of Fisker et al. [14] showed a double-peak structure (not observed in the results of the KEPLER code) with origin in the waiting points $^{30}\text{S}$ and $^{34}\text{Ar}$. A possibly higher rate would increase the production rate of $^{30}\text{S}$ and could even further pronounce this effect. This is presently under investigation. It becomes clear that studies evaluating the impact of the uncertainties of proton capture reaction rates during rp-process nucleosynthesis are necessary in order to address the nuclear physics needs of the models and improve the planning of future experiments.

5. Summary
This report summarizes selected results obtained in experiments recently performed at the NSCL on nuclei located along the rp-process. The level structure of $^{30}\text{S}$, $^{36}\text{K}$ and $^{37}\text{Ca}$ around the proton separation energy was determined with high precision. Based on the obtained data, we expect a reduction of the uncertainties in the determination of proton capture reaction rates to roughly a factor of 2 in the temperature range relevant for rp-process nucleosynthesis.

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Figure 4. (Color online) Reaction rate for the $^{20}$P(p,γ)$^{30}$S reaction at the energy range relevant for X-ray bursts. The rate derived using the spectroscopic information of Iliadis et al. [19] is shown by the light-green area. The result from Bardayan et al. [25] is shown in red. The preliminary result based on the information obtained in our measurements is shown by the black area. The uncertainties in the determination of the rate are based exclusively in the error of the resonance energies.

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