High precision measurements for the rp-process

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Abstract. The explosive nuclear burning of hydrogen at high temperatures and densities on the surface of accreting neutron stars, known as the rp-process, gives rise to a number of observable phenomena related to X-ray bursts. Recent astronomical observations provide unprecedented information, e.g. on atomic abundances in ejecta and time structure in X-ray bursts. To interpret these data requires an understanding of the nuclear processes during the explosive events and, therefore, information on the structure of unstable, proton-rich nuclei. Network model calculations show that the dominant burning processes, after breakout from the hot CNO cycles at sufficiently high temperatures, proceed via proton- and α-induced reactions. Since the reaction rates are very sensitive to the nuclear structure, shell- and statistical-model calculations are often insufficient in predicting exact reaction paths. Therefore, we have been conducting experiments using high-resolution spectrometers to search for resonances that play a role in the rp-process and determine the nuclear-structure, most importantly excitation energies, accurately above the particle thresholds. The techniques and examples of experimental results will be presented and discussed. The status and outlook of direct measurements of stellar reactions rates in inverse kinematics using planned recoil separators will be outlined.

1. Introduction
Cataclysmic nuclear explosions on the surface of accreting white dwarfs are so violent and frequent that they were already observed more than 2000 years ago by ancient Chinese observers with a keen eye on the sky. Since the light from these explosions seemed to appear and disappear, they called them guest stars. In the Middle Ages even the Europeans, with the strong belief that the heavens were eternal and unchangeable, had to admit that new stars seemed to appear suddenly and, therefore, called them novae. Once this fact was accepted, the search and regular observations of novae, as they are still called today, was continued by professional and amateur observers. An impressive example is the recording of the visual light curve of the recurring dwarf nova SS Cygni starting 1896 and continuing to this day by amateurs and published by the AAVSO [1] despite the enormous progress we have made in the instrumental observation in the last decades. Today, we know that the nucleosynthesis of the isotopes, starting soon after the Big Bang, is still happening at many locations of our universe. A number of distinct,
mostly exothermic, nuclear reactions is driving these processes. Novae are, now, interpreted as thermonuclear explosions on the surface of accreting white dwarfs in binary stars, but with the advent of satellite based X-ray spectrometers in the 1970s, a second class of much more violent explosions was discovered (now we have about 100 of these sources with multiple eruptions), which emit a strong X-ray signal and are, therefore, named X-ray bursts. These events are associated with accretion processes onto the surface of a neutron star. While novae explosions are driven primarily by the hot CNO cycle, X-ray bursts are driven by the rp-process. The rp-process was first described in 1981 by Wallace and Woosley [2] and identified as a rapid series of (p,γ) reactions and β decays. At higher temperatures, the competing (α,p) reaction (αp-process) can by-pass specific reaction paths. We will give examples how high-resolution studies of reactions can determine details of their reaction paths and help to better understand a variety of recent astronomical observations. When employed at the new generation of high-intensity radioactive beam facilities, recoil separators can directly measure the reaction rates on radioactive target nuclei that are involved in the rp-process.

2. The rp-process and rate calculations

The rp-process occurs at high temperatures (> 0.4 GK) and large densities (>10^4 g/cm^3), following the break out from the hot CNO cycles and continues rapidly, hence the name rapid-proton capture process or rp-process, along energetically possible reaction paths producing a series of proton-rich nuclei up to iron and beyond. Since the β decay of the T = 1 nuclei (22Mg, 26Si, 30S, and 34Ar) in the path have life times of the order of 1 s to 4 s, the explosive event is briefly delayed at these “waiting points” unless the reaction rate of a fast (p,γ) reaction by-passes a particular waiting point.

The conditions, where the rp-process can occur, are found at several locations in the cosmos, like in the hydrogen-accreting surface of neutron stars (X-ray bursts) of a close binary system with high-temperatures and densities. In case of a close binary-star system, the lighter companion is a red giant filled up to the first Lagrange point, where mainly hydrogen spills over into the gravity-potential well of the heavier, but smaller main star at typical rates of 10^{-8} solar masses per year, forming an accretion disk where the material slowly descends onto the surface losing angular momentum in the process. In novae, the most revealing situation arises when the plane of the binary system and the earth are nearly in the same plane leading to eclipses with characteristic timing marks, due to the entry and exit points of both stars and the bright spot, where the hydrogen plunges into the accretion disk.

In an X-ray burster, the hydrogen accumulates on the surface of the neutron star until the temperature and density are high enough for a thermonuclear ignition. Since the conditions are highly electron degenerate the released nuclear energy goes directly into a rapid increase in temperature, igniting more reactions and leading to a thermonuclear runaway.

The rate of reactions with narrow, non-overlapping resonances can be calculated as the sum over individual resonances according to the narrow-resonance formalism outlined in Ref. [3].

\[ N_A \langle \sigma v \rangle_{res} = 1.54 \times 10^{5} (\mu T_9)^{-3/2} \sum_i (\omega_i) \exp(-11.605 E_i/T_9) \] [cm^3 s^{-1} mol^{-1}], \quad (1)

with \( \mu \) the reduced mass of the target and projectile in units of amu, \( T_9 \) the temperature in units of GK, \( (\omega_i) \) the strength of the \( i^{th} \) resonance in units of eV, and \( E_i \) the energy of the \( i^{th} \) resonance in units of MeV.

If level densities are high the reaction rates can be calculated within the statistical model (Hauser-Feshbach formalism) by using computer codes like CIGAR [4], NON-SMOKER [5] or
TALYS [6]. To calculate the sequence of reaction paths all isotopes that are produced and destroyed have to be included in network calculations [7].

Equation 1 shows that the spectroscopic information of all nuclear levels involved enters in these calculations, but the rates depend exponentially and, therefore, most strongly on the resonance energy. Uncertainties in the resonance energies of the order of 100 keV can result in uncertainties of several orders of magnitude in the calculated rates. Present network calculations take as input measured parameters of single resonances where available. Otherwise, shell-model predictions with typical energy uncertainties of 100 keV or more are used. Only where level densities are high, calculations are performed using the Hauser-Feshbach statistical model. This assumption may not be always correct, in particular if selectivity reduces the level density as, e.g., in the \((\alpha,\gamma)\) or \((\alpha,p)\) reactions.

Whenever possible, excitation functions of the \((p,\gamma)\) and \((\alpha,\gamma)\) reactions are measured directly down to the lowest possible beam energy. However, low cross sections and beam-related background do not allow to measure at energies low enough to correspond to stellar temperatures and extrapolations using the R-matrix approach are necessary [8]. Moreover, this method requires stable target nuclei, and is, therefore, not available for studies of the rp-process involving unstable proton-rich nuclei. Therefore, the above-mentioned method of calculating the reaction rates on the basis of spectroscopic information of the resonance states is applied.

The contributing resonances in the compound nucleus of the stellar reaction are located within the Gamow window [3] typically \(> 1\) MeV above the p- and \(\alpha\)-thresholds depending on the stellar temperature. They show up as peaks in the spectra of the final nucleus in a suitable reaction. These reactions can be any neutron-pickup reaction with targets of the most proton-rich stable nuclei. Suitable reactions are \(2n\) pickup reactions, e.g., \((^4\text{He},^6\text{He})\) (Ref. [9]), \((p,t)\) (Ref. [10]), \(3n\) pickup reaction, e.g., \((^3\text{He},^6\text{He})\) or in special cases the \(4n\) pickup reaction \((^4\text{He},^8\text{He})\) [11].

3. Experimental Method

High-resolution spectrometers may be used to resolve and identify resonances that may be located at excitation energies up to about 12 MeV. Well-suited spectrometers are the Grand Raiden spectrometer [12, 13], at the Research Center for Nuclear Physics (RCNP) of the Osaka University in Osaka, Japan and the K600 spectrometer at iThemba LABS, Somerset West, South Africa [14]. Both spectrometers have dispersion-matched beam lines and are equipped for measurements at and near \(0^\circ\).

Figure 1 shows the cyclotron facility of RCNP including the injector AVF cyclotron, the separated-sector Ring cyclotron, the dispersion-matched WS beam line, and the Grand Raiden spectrometer, consisting of the high-resolution spectrometer used in these studies and the Large Angle Spectrometer (LAS) not used in the present studies.

Grand Raiden has a high-resolving power of \(p/\Delta p = 37000\) for a 1 mm target spot and is equipped with a fully dispersion-matched beam line. This includes the lateral-dispersion matching to be able to achieve the highest-possible spectral resolution despite the fact that the beam spread is about a factor of 10 worse compared to the resolving power. The beam line also allows for angular-dispersion matching to allow for the reconstruction of the scattering angle with a precision of \(0.4^\circ - 0.6^\circ\) at the target from measurements in the focal plane. This allows the determination of the angular distribution and hence the angular momentum for measurements at \(0^\circ\) within the angle acceptance of the spectrometer of \(\pm 1^\circ\) horizontally and \(\pm 3^\circ\) vertically. Also, the scattering angle of each event is necessary to achieve the highest-possible resolution by correcting the kinematic effect that changes the energy of the detected reaction product with angle. Typical examples are, e.g., for 200 MeV protons and \(\alpha\)-particles a beam spread of about 80 - 150 keV, while the spectrometers allow spectral resolutions of 10 - 20 keV. The difference in the kinematical shift of nuclei involved in the rp-process typically exceed these resolutions and need to be corrected using the measured scattering angle.
The highest possible resolution is not only important to separate close resonances but also to determine the excitation energies better than 10 keV. As mentioned above the main reason for the uncertainties of the calculated reaction rates are the uncertainties of the excitation energies. Our studies have shown [10] that this error can be made small compared to uncertainties from the resonance strength and spin assignments if the excitation energy can be determined with an error smaller than 2 - 5 keV. The statistical error of a peak position is given by the width of the peak divided by the square root of the number of counts. As an example, for a resolution of 40 keV and 100 counts in a peak the statistical error of the excitation energy is 4 keV. Moreover, special care has to be taken to provide a very precise energy calibration and to eliminate systematical errors. For a detailed discussion, see Ref. [10]. As an example, the focal plane of a spectrometer is known to be in first order linear in momentum. But Grand Raiden has a deviation from linearity of about 100 keV in measurements of the \((p,t)\) reaction at 200 MeV, that needs to be taken into account.
Figure 2. Measured $^{40}$Ca(p,t)$^{38}$Ca spectrum. Peaks of levels are labeled by their excitation energies in MeV and their spin and parity where known.

4. Astrophysical studies

Network calculations of the rp-process give overall agreement with measured light curves of X-ray bursts. However, ever improving astronomical observations provide data that require more detailed information about the reaction paths of the rp-process. Detailed measurements of the light curves of X-ray bursts show ripples [15] and even double and triple peaks [16] separated by several seconds that are not explained by present network calculations or dynamical models.

The two main waiting-point nuclei, $^{14}$O and $^{18}$Ne, in the CNO cycles are by-passed by the $^{14}$O($\alpha$,p)$^{17}$F($p,\gamma$)$^{18}$Ne($\alpha$,p)$^{21}$Na($p,\gamma$)$^{22}$Mg reaction sequence triggering the op-process. The time-scale for the subsequent $\alpha$p-process sequence $^{22}$Mg($\alpha$,p)$^{25}$Al($p,\gamma$)$^{26}$Si($\alpha$,p)$^{29}$P($p,\gamma$)$^{30}$S($\alpha$,p)$^{33}$Cl($p,\gamma$)$^{34}$Ar($\alpha$,p)$^{37}$K($p,\gamma$)$^{38}$Ca and the switch over to the classical rp-process is determined by the associated reaction rates. If the ($\alpha$,p) rates become low because of the increasing Coulomb barrier the reaction flow will be delayed because of the relatively slow $\beta^+$ decay of the waiting-point nuclei $^{22}$Mg, $^{26}$Si, $^{30}$S, and $^{34}$Ar. The ($\alpha$,p) reaction rates are determined by the number of resonances, the resonance energies and $\alpha$-partial widths of the $\alpha$-unbound states within about 2 MeV above the $\alpha$-thresholds of $^{30}$S, $^{34}$Ar, and $^{38}$Ca, which are 9.342, 6.739 and 6.106 MeV, respectively. Similarly, the ($p,\gamma$) reaction rates are determined according to equation 1 by the number of resonances, the resonance energies and p-partial widths of the p-unbound states within about 2 MeV above the $p$-thresholds, which are 4.399, 4.663 and 4.549 MeV, respectively. To test this model for the waiting-point $^{34}$Ar, we performed the $^{40}$Ca(p,t)$^{38}$Ca reaction.
Figure 3. Measured $^{46}$Ti($\alpha$, $^8$He)$^{42}$Ti spectrum. The peak due to the ground state and a level at around 2.2 MeV are indicated.

The ($p$,t) reaction has many advantages when measured with a spectrometer. The triton rigidity is more than a factor of 1.5 larger compared to the proton beam and other reaction products so that the beam can be stopped at the low momentum side of the dipole magnet and background from other reactions is small because they are also swept away from the focal plane. Figure 2 shows a sample spectrum, measured using the K600 spectrometer at iThemba LABS. The data analysis of this experiment is in progress.

Another astronomically interesting reaction is the $^{38}$Ca($\alpha$,p)$^{41}$Sc, which is presently assumed to be the last $\alpha$p-process in X-ray bursts based on shell-model calculations. The resonance energies are located above the $\alpha$-threshold at an excitation energy of $E_x = 5.487$ MeV in the compound nucleus $^{42}$Ti. These may be wrong by 100 - 200 keV as shown in a previous experiment [11]. Figure 3 shows the preliminary spectrum of the $^{46}$Ti($\alpha$, $^8$He)$^{42}$Ti reaction in search for the resonances using Grand Raiden at RCNP, Osaka. These experiments are very difficult because of the low cross section of about 3 nb/sr for the ground state and about a factor of 10 smaller for excited states. Also, the ($\alpha$, $^6$He) reaction has much larger yields which have to be discriminated against using the time-of-flight method and $\Delta E/E$ signal ratios from plastic scintillation detectors.

5. Outlook

We have shown that reaction studies of the nuclear structure with high-resolution spectrometers can provide valuable information to better understand the rp- and $\alpha$p-processes. Great effort has been spent to measure the reaction cross sections of the ($p$,\gamma) and ($\alpha$, \gamma) fusion reactions. This is also possible using electromagnetic recoil separators with very high mass resolution, by studying the reaction in inverse kinematics. This method has the advantage to be free of the beam related $\gamma$ background, thus allowing to measure at lower energies closer to the corresponding temperature in the stellar medium. For this purpose the St. George recoil separator was designed and built at the University of Notre Dame to study the ($\alpha$, \gamma) reaction using stable beams.

If a recoil separator is installed at a high-intensity radioactive beam facility as planned for
FRIB [17], the reaction rates of selected reactions of the rp- and αp-processes that take place in the unstable proton-rich mass region can be measured. The project SECAR has been proposed and is under design for this purpose of studying the $(p,\gamma)$ and $(\alpha, \gamma)$ fusion reactions initially at the present ReA3 facility with re-accelerated beams at MSU. When FRIB becomes available SECAR will reach its full potential with the higher intensity of radioactive beams.

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