PROCEEDINGS OF SCIENCE

High precision measurements along the *rp*-process path

D. Galaviz[*,a,b†], **M. Amthor**[a,c], **D. Bazin**[a], **B. A. Brown**[a,c], **A. Cole**[a,b], **T. Elliot**[a,c], **A. Estrade**[a,c], **Zs. Fülöp**[d], **A. Gade**[a], **T. Glasmacher**[a,c], **R. Kessler**[e], **G. Lorusso**[a,c], **M. Matos**[a,b], **F. Montes**[a,c], **W. Müller**[a], **J. Pereira**[a,b], **H. Schatz**[a,b,c], **B. Sherrill**[a,b,c], **F. Schertz**[e], **Y. Shimbara**[a,b], **E. Smith**[f], **A. Tamii**[g], **M. Wallace**[a,c], and **R. Zegers**[a,b,c]

[a] *National Superconducting Cyclotron Laboratory, 1 Cyclotron Lab, East Lansing Mi 48824, USA*
[b] *Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, Michigan 48824, USA*
[c] *Department of Physics andAstronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[d] *ATOMKI, H-4001 Debrecen, POB. 51, Hungary*
[e] *Institut für Kernchemie, University of Mainz, D-55128 Mainz, Germany*
[f] *Department of Physics, Ohio State University, Columbus, Ohio 43210, USA*
[g] *Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan*
E-mail: galaviz@nscl.msu.edu

The level structure of ^{30}S and ^{31}Cl was studied at the NSCL by using neutron removal reactions with a radioactive ^{31}S and ^{32}Cl beam, respectively. The γ-decay from excited states in ^{30}S and ^{31}Cl was measured in a Ge-detector array. The results discussed for this work may reduce the uncertainties in the determination of the ^{29}P(p,γ)^{30}S and ^{30}S(p,γ)^{31}Cl astrophysical reaction rates under *rp*-process conditions.

International Symposium on Nuclear Astrophysics — Nuclei in the Cosmos — IX
June 25-30 2006
CERN, Geneva, Switzerland

[*] Speaker.
[†] Supported by NSF Grants No. PHY-01-10253 (NSCL) and No. PHY-02-016783 (JINA)

PoS(NIC-IX)099

1. Astrophysical motivation

A new era in the astronomy and astrophysics was initiated with the first observation of Gamma-ray bursts of cosmic origin [1]. This lead to searches of similar objects in the universe and the explanation of their origin. Today the number of objects observed with X-ray observatories such as RXTE, Chandra and XMM-Newton has increased tremendously. The improved precision allows for distinction between the origin and the nature of the different X-ray and Gamma-ray sources.

Type I X-ray bursts are classified within X-ray sources as thermonuclear explosions on the surface of a neutron star in a companion system with a main sequence star. The accreted material, mainly hydrogen and helium, is accumulated in a disc and dumped on top of the neutron star; it remains here until the temperature and density are high enough to ignite the material and originate the explosion. The resulting X-ray burst lasts 10 – 100 s and is powered by thermonuclear reactions. Temperatures of up to 2 GK and densities $\rho \geq 10^5$ g/cm^3 can be reached during the so-called *rp*-process [2, 3]. Under these conditions, a series of mainly (α,p), (p,γ) reactions and β^+-decays control the production of neutron–deficient nuclei up to the mass region $A \approx 100$, where the *rp*-process is predicted to end [4].

The reaction path and the final abundances in the *rp*-process are determined by the nuclear properties of the neutron–deficient nuclei involved in the process. Masses are an important component, as they determine the *waiting-points* of the process (nuclei with particulary slow β^+ decays for the *rp*-process to proceed), as well as β^+-decay half lives. A precise knowledge of the level density above the particle threshold is important to derive particle-capture reaction rates, and thus enable a correct description of the process path under astrophysical conditions. Level densities just exceeding the proton threshold in *rp*-process nuclei close to the proton drip line are not high enough to calculate reaction rates using statistical models. A precise knowledge of the level structure for these nuclei over the proton threshold is neccesary to calculate resonant (p,γ) reaction rates. The resonant proton capture rate at temperature T is given by:

$$< \sigma v >_{(p,\gamma)} = \left(\frac{2\pi}{\mu kT}\right)^{3/2} \hbar^2 \frac{2J_f+1}{(2J_p+1)(2J_i+1)} \frac{\Gamma_p(E_R)\,\Gamma_\gamma(E_x)}{\Gamma_{total}(E_R,E_x)} \exp\left(-\frac{E_R}{kT}\right) \tag{1.1}$$

with k as the Boltzman constant, μ the reduced mass, and E_X the energy of the level. The reaction rate is dependent on angular momenta (J_i, J_p, J_f) and widths (Γ_γ, Γ_p, Γ_{total}) of the initial (i), proton (p), and final states (f), and furthermore shows an exponential behaviour to the resonance energy E_R. In addition, Γ_p also depends exponentially on E_R. Precise knowledge, therefore, of both excitation energy of the level and the masses of the nuclei involved is necessary to reduce the uncertainty in the determination of the reaction rate.

2. Experimental method

Scarcity of experimental information on proton-capture reactions along the *rp*-process path, with the exception of ^{21}Na(p,γ)^{22}Mg [5] and ^{13}N(p,γ)^{14}O [6], and the limited understanding of the level structure above the proton threshold of exotic proton-rich nuclei, forces the use of theoretical models to predict nuclear properties of these nuclei. Shell model calculations with developed effective interactions for nuclei in the sd-shell can be used. Normally uncertainties of about 100 keV in the prediction of excited level energies might translate into several orders of magnitude in the determination of the resonant (p,γ) reaction rate, as shown in Fig. 1 for the ^{29}P(p,γ)^{30}S reaction. Two levels located above the proton separation energy (S$_p$(^{30}S) = 4400 keV) were predicted at 4733 and 4888 keV using the shell model calculations [7].

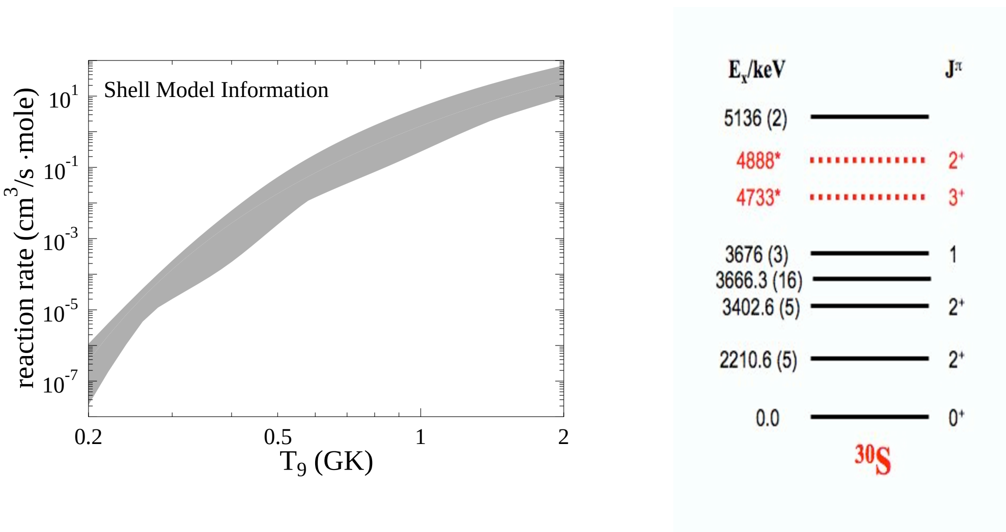

Figure 1: The ^{29}P(p,γ)^{30}S reaction rate (left) at astrophysically relevant temperatures and the present knowledge on ^{30}S [8]. The dashed area presents the uncertainty in the determination of the reaction rate when considering an accuracy of 100 keV in the prediction of the two levels above the particle threshold in ^{30}S [7].

The level structure of ^{30}S was studied at the NSCL to improve the accuracy in the determination of the reaction rate under astrophysical conditions. The experimental setup is described in [9]. A stable ^{36}Ar beam (150 MeV/nucleon) was fragmented on a 1061 mg/cm^2 ^{9}Be target, producing a ^{31}S beam (71 MeV/nucleon), which was selected in the A1900 fragment separator [10]. The ^{31}S was transported to the target position of the S800 magnetic spectrograph [11] and interacted with a 180 mg/cm^2 polypropylene target, producing ^{30}S in a neutron removal process (neutron-knockout on ^{12}C, (p,d) reaction on ^{1}H). The ^{30}S nuclei were identified in the focal plane of the S800. The emitted γ-rays were measured using 17 detectors of the Segmented Germanium Array (SeGA) [12].

3. Preliminary results

The Doppler-corrected γ-ray measured in coincidence with the identified ^{30}S nuclei are shown in Figure 2. The decay from the first and second excited states in ^{30}S is clearly observed in the spectrum; further analysis of all other γ-rays is ongoing.

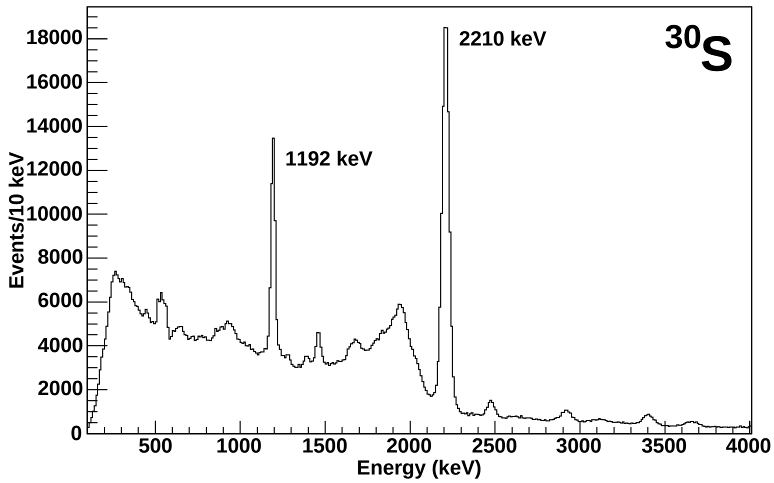

Figure 2: Preliminary Doppler-corrected γ-ray spectrum from the decay of excited states in ^{30}S. The transition from the first and second excited states in ^{30}S can be clearly observed.

This investigation may provide the necessary information to determine the level structure of ^{30}S above the proton threshold with higher precision, and therefore reduce the uncertainty in the determination of the ^{29}P(p,γ)^{30}S reaction rate under *rp*-process conditions.

References

[1] R. W. Klebesadel, I. B. Strong, R. A. Olson, Astrophys. J. **182** (1973) L85–L88.

[2] R. K. Wallace, S. E. Woosley, Astrophys. J. Suppl. **45** (1981) 389.

[3] H. Schatz *et al.*, Phys. Rep. **294** (1998) 167.

[4] H. Schatz *et al.*, Phys. Rev. Lett. **86** (2001) 3471.

[5] S. Bishop, *et al.*, Phys. Rev. Lett. **90** (2003) 162501.

[6] P. Decrocka, *et al.*, Phys. Lett. B **304** (1993) 50.

[7] C. Iliadis *et al.*, Astrophys. J. Suppl. **134** (2001) 151–171.

[8] P. M. Endt, R. B. Firestone, Nucl. Phys. **A 633** (1998) 1.

[9] R. R. C. Clement *et al.*, Phys. Rev. Lett. **92** (2004) 172502.

[10] D. J. Morrisey, *et al.*, Nucl. Instr. and Meth. **B 204** (2003) 90.

[11] D. Bazin, *et al.*, Nucl. Instr. and Meth. **B 204** (2003) 629.

[12] W. F. Mueller, *et al.*, Nucl. Instr. and Meth. **A 466** (2001) 492.