The p-process Workshop

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Max-Planck Institut fuer Extraterrestrische Physik (MPE)

Book of abstracts

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Astrophysical models can explain the origin of most nuclei beyond the iron group by a combination of processes involving neutron captures on long (s-process) or short (r-process) time scales. However, 32 proton-rich stable isotopes between 74Se and 196Hg cannot be formed in these neutron capture processes, because they are either shielded by stable isotopes from the r-process decay chains or lie outside the s-process flow. These isotopes, which are ascribed to the so-called "p-process", are 10 to 100 times less abundant than their s- and r-process neighbors. So far, the astrophysical site of the p-process is still under discussion, since the solar p-abundances cannot be completely described by current models. Historically, the p-process was thought to proceed via proton captures, but a plausible site with the required amount of free protons could not be identified. Moreover, elements with large Z cannot be produced by proton captures because the temperatures necessary to overcome the Coulomb repulsion favor photodisintegration rather than charged-particle capture. The most plausible astrophysical site is the explosively burning Ne/O layer in core collapse supernovae, which is heated to ignition temperatures by the outgoing shock front. In this high-temperature environment proton-rich nuclei are produced by sequences of photo-dissociations and beta+ decays. In stars 20 times more massive than the sun the p-process temperatures for efficient photo-disintegration are already reached at the end of hydrostatic Ne/O burning. This mechanism is also called "gamma process" because proton-rich isotopes are produced by (gamma,n) reactions on pre-existing seed nuclei from the s- and r- processes. When (gamma, p) and (gamma,alpha) reactions become comparable or faster than (gamma, n), the reaction path branches out from the initial isotopic chain and feeds nuclei with lower atomic number Z. While photodisintegration dominates in the early, hot phase, the initially released neutrons can be recaptured at a later time, when the material cools down after the passage of the shockwave. The typical p-process abundance pattern exhibits maxima at 92Mo (N=50) and 144Sm (N=82). The solar abundances of the p-nuclei are reproduced by current models of the gamma process within factors of two to three on average, except for two regions with nuclei of A <100 and 150 < A < 165. The most abundant p-isotopes, 92,94Mo and 96,98Ru, are significantly underproduced because appropriately abundant seed nuclei are missing. Alternative processes and sites have been proposed in order to explain this deficiency, i.e. reactions induced by the strong neutrino fluxes in the deepest ejected layers of core-collapse supernovae (the nu p process), or explosive hydrogen burning in proton-rich, hot matter accreted onto the surface of neutron stars (the rp process). An alternative site for additional production of the 150 < A < 165 has not been suggested so far. A few p-nuclides may also be produced by neutrino reactions during the gamma process. This "nu process" could be the origin of the odd-odd isotopes 138La and 180mTa, which are strongly underproduced in the gamma process. The abundances of both p-nuclei may be explained by neutrino scattering on their abundant neighbor isotopes to states above the neutron emission threshold. The isotopes 152Gd, 164Er, and 180mTa were sometimes also considered as p-nuclei but it was found that significant fractions are produced indeed by the s-process. The fact that self-consistent studies of the gamma process have problems to synthesize the p-nuclei in the mass regions A < 124 and 150 < A < 165 may result from difficulties related to the astrophysical models as well as from systematic uncertainties of the nuclear physics input. Therefore, the improvement of nuclear reaction cross sections is crucial for further progress in p-process models, either by directly replacing theoretical predictions by experimental data or by testing the reliability of predictions if the relevant energy range is not accessible by experiments. Experimental data will necessarily remain a complement to the indispensable theoretical predictions for the vast majority of the mostly unstable isotopes in the p-process network, which are not accessible to cross section measurements with present experimental techniques. Nevertheless, these data provide important tests of existing calculations in the Hauser-Feshbach statistical model, i.e. with the codes NON-SMOKER or MOST. This workshop brings together experimentalists, theoreticians, and stellar modellers to discuss about actual problems, achievements, and the future in the field of p-process nucleosynthesis.

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Mass measurements of exotic nuclides along the rp-process path at SHIPTRAP

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The masses of proton-rich nuclides in the element range from Sr to Tc were measured with the Penning trap mass spectrometer SHIPTRAP [1] at GSI. These nuclei were produced in the fusion-evaporation reaction 36Ar + 54Fe at energies of 5.0 and 5.9 MeV/u and separated by the velocity filter SHIP [2]. Their masses were measured with relative accuracies ranging from 5·10-8 to 2·10-7.

The masses of 85,86,87Mo and 87Tc were measured for the first time in a direct measurement; 85Mo and 87Tc are the heaviest N=Z+1 nuclides measured in a Penning trap. Results from this experiment show a shift of the mass surface towards less-bound nuclei. Shifts in the mass excess values of up to 1.6 MeV is observed compared to the values of the 2003 Atomic Mass Evaluation (AME 2003) [3]. Previous experiments at SHIPTRAP and JYFLTRAP show a similar trend for neighboring nuclides, but less strong [4,5]. Even though the masses generally are shifted in the same direction, the changes also influence the proton and neutron separation energies. For example, the proton separation energy of 87Tc has now been determined to be only half that of the extrapolated value given in the AME 2003.

The newly measured and extrapolated mass data serve as important input for improved calculations on the rp-process path. Preliminary data on mass excess, separation energies, and their impact on rp-process network calculations will be discussed. Perspectives and developments for future mass measurements at SHIPTRAP targeting N=Z nuclei will be outlined.

[1] M. Block et al., Eur. Phys. J. D 45 (2007) 39.
[2] S. Hofmann and G. Münzenberg, Rev. Mod. Phys. 72 (2000) 733.
[3] G. Audi et al., Nucl. Phys. A 729 (2003) 337.
[4] A. Kankainen et al., Eur. Phys. J. A 29 (2006) 271.
[5] C. Weber et al., Phys. Rev. C 78 (2008) 054310.

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(p,gamma) measurements for p-process nucleosynthesis with the ESR at GSI

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Experimental studies on rp-process nuclei at the NSCL

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Type I X-ray bursts are thermonuclear runaways that occur on the surface of neutron stars in binary systems with low-mass companions. These systems, in some cases, host the so-called rapid proton capture process (rp–process) [1,2]. Under high temperature (T ~2 GK) and density (rho> 1E5 g/cm3) conditions in the burning layer, the nuclear reaction network of the rp- process runs close to the proton drip-line via series of (alpha ,p) and (p,gamma) reactions, and subsequent beta+ decays, thus creating proton-rich nuclei. The modeling of these astrophysical objects and the correct description of their observables (i.e. light emission curves) relies on correct nuclear physics input.
Concerning the mass region A >40, proton capture rates are often dominated by a few resonances and therefore statistical methods can not be applied. In order to reduce the uncertainties in the calculation of resonant proton capture rates, neutron removal experiments on exotic beams have been performed at the National Superconducting Cyclotron Laboratory at Michigan State University to precisely determine the excitation energy levels of nuclei located along the rp–process path [3,4,5].
This contribution presents the results obtained from those experiments.

[1] R. K. Wallace, S. E. Woosley, Astrophys. J. Suppl. 45 (1981) 389.
[2] H. Schatz et al., Phys. Rep. 294 (1998) 167.
[3] R. R. C. Clement et al., Phys. Rev. Lett. 92 (2004) 172502.
[4] D. Galaviz et al., to be submitted
[5] A. M. Amthor, Ph. D. Thesis, Michigan State University, 2008

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Alpha-induced reaction cross section measurements on 151Eu

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In order to extend the available experimental database of alpha-induced reactions relevant for the p-process towards the heavier mass region, the cross section of the 151Eu(alpha,gamma)155Tb and 151Eu(alpha,n)154Tb reactions has been measured using the activation technique. The cross sections have been detemined in the center-of-mass energy range of 11.2 – 17 MeV and 12.3 – 17 MeV for the (alpha ,n) and (alpha ,gamma) channels, respectively.
Some details of the measurement will be presented in the talk with emphasis on the special experimental requirements of an activation experiment.
Preliminary results and the comparison with statistical model calculations will also be shown.

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Opportunities of in-beam experiments for the astrophysical p process

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The p-process is the most promising astrophysical scenario for the nucleosynthesis of about 35 proton-rich nuclei referred to as p nuclei. This process involves an extensive reaction network of about 2000 nuclei and more than 20000 reactions, especially photodisintegration reactions, under explosive physical conditions. The huge number of reaction rates are mainly adopted from Hauser-Feshbach calculations. Hence, experimental data are essential to put stringent constraints on the nuclear models required for these calculations. It is the major aim of experimental p-process studies to improve descriptions for optical model potentials, nuclear level densities and photon strength functions.
Experiments on (p,gamma) and (alpha,gamma) reactions are a dedicated approach to study these nuclear properties at astrophysically relevant energies and, thus, a large number of these experiments have been performed in the last years. Despite these efforts, the data base is still not sufficient to derive reliable global nuclear models for reaction-rate calculations, and additional data have to be provided.
In this contribution, we will give an overview of different experimental methods that have been applied so far to study proton- and alpha-induced capture reactions. The advantages and limitations of both the activation and in-beam technique will be discussed. In this context, we will present the gamma-detector array HORUS at the ion TANDEM accelerator of the University of Cologne, which allows to perform highly-sensitive in-beam experiments on reactions of astrophysical interest. An outlook will be given on the unique experimental opportunities for future p-process studies that are provided by this sophisticated facility.
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A global study of the electric dipole strength in heavy nuclei

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The gamma ray strength function of heavy nuclei is an important quantity to determine their reaction rates in in high temperature environments envisioned in explosive nucleosynthesis. Especially p-process nuclides are formed through sequences of photodisintegrations from sand r-process seeds. In these reactions the gamma ray strength function around the neutron separation energy on the low energy side of the giant dipole resonance plays a decisive role. Recently, photon scattering and photodisintegration experiments [1] have been made at the ELBE accelerator at FZ Dresden Rossendorf in this energy range and the gamma ray strength function has been investigated.
Based on these data a new parameterization [2] of the electric dipole strength is proposed which can be of great importance for cosmic nucleosynthesis calculations. With only two new parameters it allows us to describe the dipole strength in all heavy nuclei with A> 80. Although it differs significantly from previous parameterizations it holds for spherical, transitional, triaxial and well deformed nuclei. The GDR spreading width depends in a regular way on the respective resonance energy, but it is independent of the gamma ray energy.

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[2] A.R. Junghans et al. Phys. Lett. B 670 200 (2008).

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Proton-induced reactions for the astrophysical p-process

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ATOMKI has a long range program, supported by the European Research Council, to study reactions relevant to p-process using low energy accelerators.
In addition to the alpha-induced reactions, proton-induced cross section data can test the reliability of the model calculations in the proton rich region as well as provide experimental information directly relevant to the p-process. Recent advances involving also the study of (p,n) reactions underline the importance of the stellar enhancement factor and call for a modi ed optical parameter set.

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The (n, gamma) Cross Sections Of Heavy p-Process Nuclei

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The neutron capture cross sections of proton-rich nuclei are important for the nucleosynthesis of the heavy elements in the p process. Aspects of (n,gamma) reactions in the p process refer to the competition with (gamma,n) reactions, which affects the photodisintegration flux towards lighter nuclei, and to the formation of the final p-process abundances during the freeze-out phase. However, the knowledge of neutron capture cross sections of the rare proton-rich isotopes is very limited and still missing in many cases.

First measurements of the stellar neutron capture cross sections are reported for the stable p isotopes 168Yb, 184Os, and 196Hg. For 180W and 190Pt the uncertainties of 11% and 27% from previous easurements could be significantly reduced. The present measurements were based on the activation technique. Neutrons were produced at the Karlsruhe Van de Graaff accelerator via the 7Li(p, n)7Be reaction.
For proton energies just above threshold, one obtains a neutron spectrum similar to a Maxwellian distribution for kT = 25 keV. This quasi-stellar neutron spectrum allowed us to measure the Maxwellian averaged cross sections directly.
The experimental results were extrapolated from kT = 25 keV to lower and higher temperatures.

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Detection, halflife and production of p-process nuclide 146Sm: progress report

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The 146Sm nuclide (t1/2= 1.03x10^8 a) belongs to the small family of nuclides produced by the nucleosynthesis p-process . Its presence as live radionuclide in the Early-Solar System was established by the study of isotopic anomalies of its 142Nd alpha daughter in meteorites. Interestingly, a difference in 142Nd isotopic signatures has been also discovered between terrestrial and chondritic material, leading to new
insight in the chronology of planetary formation. We have developed a method for 146Sm detection by positive-ion high-energy accelerator mass spectrometry at the Argonne ATLAS facility, using a gas-filled magnet for the isobaric 146Sm-Nd separation. 146Sm samples were produced by (gamma,n), (n,2n) and (p,2nEC) activations of enriched 147Sm targets. A new determination of the 146Sm half-life is in progress, based on the measurement of the 146,147Sm alpha activities of the irradiated targets and the AMS determination of their 146Sm/147Sm atom ratio. Special attention is given to the absolute determination of this ratio and methods under development will be described. The present detection sensitivity of the 146Sm/147Sm ratio of the order of 10^-12 will allow us to measure the 147Sm(gamma,n)146Sm reaction cross section, of importance in the p-process synthesis of 146Sm. Activations of 147Sm targets by 50, 25
and 10-MeV electron bremsstrahlung have been performed and the AMS measurements are planned.

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Study of 69Br Proton Emission and the rp-Process 68Se Waiting Point

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A complete understanding of the synthesis of the elements is one of the main outstanding questions in nuclear astrophysics. A number of nucleosynthesis processes are known and to a reasonable extent account for much of the observed solar abundances of nuclei. However, there are a number of elements that can only be produced via processes involving proton rich nuclei. The rapid proton capture or rp-process, is one such mechanism which occurs along the proton drip-line whereby fast proton captures on seed nuclei followed by beta-decay allow for the production of elements possibly as heavy as Te. Type I X-ray bursts are thought to be key sites for this process. To realistically model the rp-process in these systems experimental data such as masses, lifetimes, and proton capture rates along the proton drip-line are required. Such data are currently lacking for many of these nuclei.

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The 68Se waiting point is of particular interest, where a long beta-decay half-life coupled with inhibited proton capture restricts the amount of material that is processed beyond mass 68 in the rp-process. However, the reaction rate for the 2p-capture process 68Se+p -> 69Br+p -> 70Kr depends exponentially on the Q-value and may bypass the waiting point. This Q-value is poorly constrained. We have performed an experiment to measure Q-values of proton unbound states of exotic nuclei at the National Superconducting Cyclotron Laboratory (NSCL) Coupled Cyclotron Facility. The experiment was designed to reconstruct the decays of proton unbound nuclei, specifically 69Br, by detecting the decay protons using the MSU High Resolution Array (HiRA) in coincidence with a heavy residue, e.g. 68Se, which is measured in the large acceptance S800 magnetic spectrograph. The fi rst direct measurement of ground state proton emission from 69Br and general implications for the rp-process will be discussed.

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New capabilities for p-process measurements with re-accelerated rare isotope beams at ReA3

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Proton, neutron and alpha-particle capture reactions are the main contributors towards the understanding of the p-process nucleosynthesis. Although the reactions involved in this process are mainly photodisintegrations, measuring the inverse reactions can be even more helpful than the measurement of the gamma
-induced reactions themselves. Recently there have been major experimental efforts
to measure (p,
gamma) and (alpha ,gamma
) reactions in the medium heavy mass region, at astrophysicaly relevant energies. These investigations, however, are limited in nuclei along the valley of stability. The
development of re-accelerated rare isotope beams enables the study of such reactions for unstable nuclei in inverse kinematics. The small cross sections of these reactions in combination with the low beam intensities of rare isotope beams make such experiments difficult and the use of a high efficiency detection system is crucial. A 4pi
ray calorimeter would be ideal for such measurements
since its large angular coverage enables the efficient summation of the emitted
rays. The Q-value
of most of the relevant reactions is large enough that the resulting summing peak would be expected at high energies, where the
ray spectrum is practically background free. This method has been
used successfully in experiments with stable beams and is a promising technique to be applied for p-process measurements at the National Superconducting Cyclotron Laboratory with rare isotope beams from ReA3.

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p-process simulations with an updated reaction library

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We have performed p-process simulations with an updated version of the Basel reaction library [1,2] including all (n,gamma) cross sections from the Karlsruhe Astrophysical Database in Stars project (v0.2) [3]. The simulations were carried out with a parametrized supernova type II shock front model ('gamma -process') of a 25 solar mass star and compared to recently published results of Rapp et al. [4].

A decrease in the normalized overproduction factor could be attributed to lower cross sections of a significant fraction of seed nuclei located in Bi and Pb regions around the N = 126 shell closure.
The next step is the use of the JINA Reaclib [5] with inclusion of the most recent KADoNiS update (v0.3) and p-process reactions [3].

[1] I. Dillmann, T. Rauscher, M. Heil, F. Kaeppeler, W. Rapp, and F.-K. Thielemann, J. Phys. G: Nucl. Part. Phys. 34 (2007); I. Dillmann et al., in preparation for Phys. Rev. C
[2] Basel reaction library, online at http://download.nucastro.org/astro/reaclib/
[3] The Karlsruhe Astrophysical Database of Nucleosynthesis in Stars, online at www.kadonis.org
[4] W. Rapp, J. Goerres, M. Wiescher, H. Schatz, and F. Kaeppeler, Astrophys. J. 653 (2006) 474
[5] JINA Reaclib database, online at http://www.nscl.msu.edu/~nero/db/

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Status of the p-process database in KADoNiS

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A short overview is given about ongoing activities concerning the p-process library in the Karlsruhe Astrophysical Database of Nucleosynthesis in Stars (www.kadonis.org). For this project a collaboration with the ATOMKI in Debrecen has been established.

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The rp-process: a short introduction

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The nu~p-process in core-collapse supernovae

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Recent hydrodynamic simulations of core-collapse supernovae with accurate neutrino transport suggest that the bulk of the neutrino-heated ejecta is proton rich, in which the production of some interesting proton-rich nuclei is expected. However, there are a number of beta-waiting points that prevent the production of heavy proton-rich nuclei beyond iron in explosive events such as core-collapse supernovae. Recent studies have shown that the rp-process (or nup-process) takes place by bypassing these waiting points via neutron-capture reactions with the help of neutrino capture on free nucleons during the early phase of the neutrino-driven winds of core-collapse supernovae. I will discuss on the role of the supernova dynamics as well as the sensitivities of some key nuclear reactions to the efficiency of the nup-process.

gamma process III: photo reactions / 17

Photon-induced experiments for the p process

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