ESF/PESC Exploratory Workshop on p-Process Nucleosynthesis

Vravron, Attika, Greece, April 18-21, 2002

CONVENOR

Dr. Sotirios V. Harissopulos

ORGANIZING COMMITTEE

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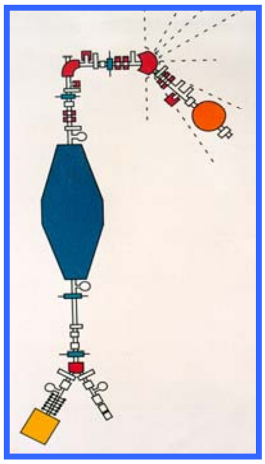


Dedicated to the memory of
THEMIS PARADELLIS
our beloved colleague and friend

Dr. Nikiforos-Themistokles PARADELLIS (1942-2002)
Director of Research
President of the Hellenic Nuclear Physics Society

Themis Paradellis was born in Cairo on the 4th of July 1942. He obtained his Diploma in Physics from Athens University in 1965. During his studies, he exploited the broad scope offered by the curriculum and complemented it with study to obtain sufficient depth in various science subjects (e.g. chemistry or astronomy) which he used during his carrier. He worked for two years as an assistant in the Physics Dept. of the University and then went to Canada where he obtained his Master's Degree (1967) and PhD (1970) from the University of Saskatchewan. Until 1972 he stayed as a Post Doctoral Fellow at the Foster Radiation Lab, Mac Gill University. He then responded to the call and came to the Tandem Accelerator Laboratory, of the National Research Centre "Demokritos" preferring it from other tempting proposals (e.g. MIT). He devoted his effort, and his life, to this Laboratory and contributed largely in making it a scientific institution internationally recognized for the quality of its work.

The curriculum of Themis Paradellis is rich in numbers of publications, as well as, in the variety of his interests. He started with Nuclear Spectroscopy using γ-rays where he contributed, not only by measuring decay schemes and nuclear level properties, but also by interpreting the data in terms of nuclear models and refining the measuring and analysis techniques. He also made some digressions and contributed to reactor physics, heavy ion reactions or novel methods for isotope production.

He felt very early the need to use his knowledge to applications, starting the field of x-ray microanalysis with applications in medicine, archaeometry, material science and the environment, and complementing it with studies of basic questions of the interaction of X-rays and ion beams with matter.

The attitude towards his research students is very accurately described by the German term "Doktorvater". He allowed them to develop free initiative, even commit mistakes, but they always felt that he was there to guide them whenever they were lost.

He approached his latest interest, Nuclear Astrophysics, with the usual ardor and commitment, continuing his tradition for accurate and reliable measurements, which have placed the Laboratory in a respectable position within the community gathered for this workshop. With his usual, intensive and meticulous approach, he attacked also the task of evaluation of cross sections, this very important product of our combined efforts.

The loss of Themis Paradellis is painful for the Tandem Accelerator Laboratory of NCSR "Demokritos". We will remember him as a highly esteemed scientist, as a wise colleague full of new ideas and as a humorous friend. Without him, we will have to increase our effort to keep this Laboratory in the position it has acquired in the international scientific community.

Scope of the Workshop

The ESF Exploratory Workshop on "p-process nucleosynthesis" refers to the interdisciplinary scientific domain of Nuclear Astrophysics resulting from the very special interplay between nuclear physics and astrophysics. Nuclear astrophysicists have made an impressive progress in improving our understanding of the solar system nuclidic composition. However, there remain many puzzles that challenge the basis of theoretical modeling, as well as of experimental approaches. Among these puzzles, the origin of the so-called *p nuclei* is a major one.

In the development of the theory of nucleosynthesis, it was realized very early that the production of the p nuclei requires a special mechanism termed *p process*, in which various nucleosynthesis scenarios are involved. One of the most important goals of all models of p-process nucleosynthesis is the description of the abundances of the p-nuclei. In this direction various p-process calculations have been successful, however, there are still many cases where discrepancies between predicted and observed abundances remain unresolved. These discrepancies could be attributed to uncertainties in the astrophysical modeling of p process, as well as to uncertain nuclear physics data entering the calculations. Clearly, among the most challenging interdisciplinary tasks to be carried out during the proposed workshop is to evaluate to what extent nuclear physics uncertainties can affect the predictive power of the astrophysics models related to p-process.

The present workshop is the first of its kind. It focuses on a topic that has been, until now, only inadequately covered by some international nuclear physics conferences. This is largerly due not only to time limitations present in such conferences but also to the poor knowledge that both nuclear physicists and astrophysicists have of the p-process. However, the interest of the nuclear astrophysics community has increased significantly over the last five years. This increasing interest is documented by an augmenting number of relevant publications.

European teams working in the scientific field of heavy element nucleosynthesis are recognized by the international Nuclear Astrophysics community to have the leading role. A considerable contribution to this european scientific status has been made by a few theoreticians from the discipline of astrophysics and of course by a number of small nuclear physics laboratories spread throughout Europe, with very low national and european funding. In most of these labs experimental work has been carried out by using "small" accelerators, amongst which however, very few remain in operation nowadays.

So far, the work that is being carried out by European groups is uncoordinated. In view, however, of the extensive number of nuclear data necessary for p-process studies, the setting up of a coordinated interdisciplinary research programme involving various European groups is required. In this respect, the present workshop aims at giving the opportunity to European teams to discuss common problems, identify joint projects for the future, set the proper guidelines and explore the possibility of setting up soon a large European network aiming at contributing to the investigation of modern scientific problems and theories in the field of Nuclear Astrophysics. The results of the proposed workshop are expected to have a long lasting impact on studies related to heavy element nucleosynthesis at an international level.

The importance of bringing together, for the first time, scientists from different disciplines, who are enganged in research activities on p-process nucleosynthesis, has been readily recognized by the European Science Foundation, which has generously supported the present workshop. This support is warmly acknowledged by the Convenor and the Organizing Committee. This occasion will certainly give the opportunity to all participants to enhance the leading role of Europe in the field of Nuclear Astrophysics.

Sotirios V. Harissopulos
Dr. rer. nat.
Convenor of the Workshop

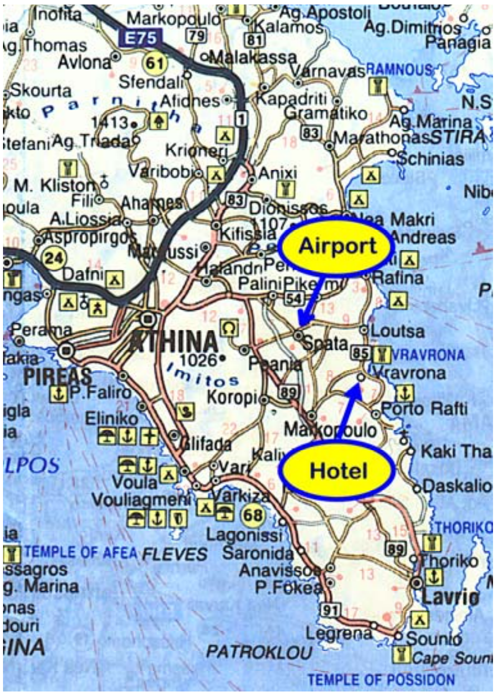
ESF Exploratory Workshop on p-Process Nucleosynthesis

Vravron, Attika, Greece, April, 18-21, 2002

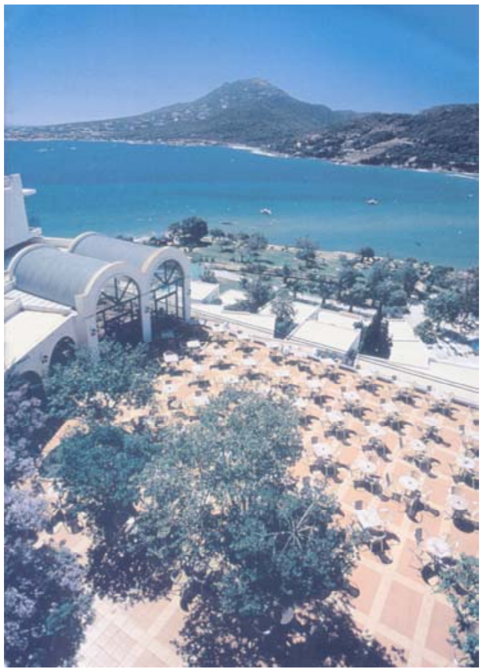
The Venue

The Workshop takes place at the “Mare Nostrum” Club Med Hotel located at the coast of Vravrona. As shown on the map of Attica, the Hotel is located close to the new airport “Eleftherios Venizelos” at Spata, at a distance of less than 10 Km. More information on “Mare Nostrum” can be found at http://www.clubmed.fr (search for “Mare Nostrum”). If you want to contact the hotel please use: Tel: (+30)-2940-48412, Fax: (+30)-2940-47790

Map of Attika



Workshop Venue



The Organizing Committee

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ESF Exploratory Workshop on p-Process Nucleosynthesis

Vravron, Attika, Greece, April 18-21, 2002

Convenor : Dr. S. Harissopulos

SCIENTIFIC PROGRAMME

18-04-2002 THURSDAY

Late afternoon Registration and welcome cocktail

19-04-2002 FRIDAY

09.00–09.30	Welcome addresses	
	Prof. E. Biémont, ESF Representative - Dr. S. Harissopulos, Workshop's Convenor	
09.30– 11.15	SESSION I	p nuclei (1) : abundances, production processes
		(Chair: Nikos Prantzos, IAP, Paris, France)
	09.30-10.15	Marcel Arnould (IAA, ULB, Bruxelles, Belgium)
		p-process : an overview
	10.15 - 10.45	Thomas Rauscher (Dept. Physik, Uni Basel, Basel, Switzerland)
		p-process in type II supernovae
	10.45 - 11.15	Vincenzo Costa (Osservatorio Astrofisico di Catania, Catania, Italy)
		The p-process in type II supernovae: current status
11.15 – 11.45	Coffee break	
11.45 – 13.15	SESSION II	p nuclei (2) : abundances, key reactions
		(Chair: Marc Rayet, IAA, ULB, Brussels, Belgium)
	11.45 – 12.15	J. Wolfgang Hammer (IfS, Uni Stuttgart, Stuttgart, Germany)
		Reaction rates of the key reactions of stellar nucleosynthesis
	12.15 - 12.45	Franz Kaeppeler (IK, FZK, Karlsruhe, Germany)
		s- and p-interferences
	12.45 - 13.15	Ulrich Ott (MPI-Chemie, Mainz, Germany)
		p-process and related isotope anomalies in meteorites
13.15 – 15.00	Lunch	
15.00 – 16.30	SESSION III	Nuclear physics aspects of p process (1)
		(Chair: F.-K. Thielemann, Uni Basel, Basel, Switzerland)
	15.00 - 15.30	Stephane Goriely (IAA, ULB, Bruxelles, Belgium)
		Impact of nuclear uncertainties on the p-process nucleosynthesis
	15.30 - 16.00	Magne Guttormsen (Dept. of Physics, Univ. Oslo, Oslo, Norway)
		Extraction of level densities from primary γ-spectra
	16.00 – 16.30	Sunniva Siem (Dept. of Physics, Univ. Oslo, Oslo, Norway)
		Level densities and γ-strength functions: important quantities in nucleosynthesis
16.30 – 17.00	Coffee break	
17.00 – 18.00	SESSION IV	Nuclear physics aspects of p-process (2)
		(Chair: Claudio Spitaleri, LNS-INFN, Catania, Italy)
	17.00 – 17.30	Stephane Hilaire (CEA/DAM, Bruyères-le-Chatel, France)
		Macroscopic level densities far from the valley of stability
	17.30 - 18.00	Paraskevi Demetriou (INP, NCSR "Demokritos", Athens, Greece)
		Global α-particle potentials for astrophysical applications

20-04-2002 SATURDAY

09.00– 11.00 SESSION V Experimental aspects of p-process (1) :
(Chair: Filippo Terrasi, II Univ. Napoli,/INFN, Napoli, Italy)

09.00 -09.30 Hiroaki Utsunomiya (Dept. Physics, Konan Univ., Kobe, Japan)
Photoneutron cross sections for the p process

09.30 -10.00 Andreas Zilges (IKP, TU Darmstadt, Darmstadt, Germany)
Investigation of photon induced reactions during nucleosynthesis

10.00 - 10.30 Peter Mohr (IKP, TU Darmstadt, Darmstadt, Germany)
(γ,α)-reactions and α-potentials

10.30 - 11.00 Endre Somorjai (ATOMKI, Debrecen, Hungary)
Experimental aspects of p-process studies using p- and α-beams

11.00 – 11.30 Coffee break

11.30– 13.00 SESSION VI Experimental aspects of p-process (2) :
(Chair: Adelaide Pedro de Jesus, CFN, Univ. Lisboa, Portugal)

11.30 – 11.50 Wolfgang Rapp (IK, FZ Karlsruhe, Karlsruhe, Germany)
Alpha and neutron induced reactions in ^{96}Ru and ^{98}Ru

11.50 - 12.10 Gyorgy Gyürky (ATOMKI, Debrecen, Hungary)
(p,γ) and (p,n) cross sections in Se isotopes

12.10 - 12.25 George Kriembardis (INP, NCSR "Demokritos", Athens, Greece)
Cross section measurements of ^{78}Se(p, γ) and ^{80}Se(p,γ) reactions

12.25 - 12.40 Stratos Galanopoulos (INP, NCSR "Demokritos", Athens, Greece)
(p,γ) cross sections in Sr isotopes

12.40 - 13.00 Panagiota Tsagari (INP, NCSR "Demokritos", Athens, Greece)
(p,γ) rates of ^{89}Y relevant to p process

13.00 – 15.00 Lunch

15.00 – 16.00 SESSION VII (Chair: Stathis Kossionides, NCSR "Demokritos", Athens)

15.00 – 15.30 Sotiris Harissopulos (INP, NCSR "Demokritos", Athens, Greece)
Capture reactions relevant to p-process : present status and future needs

15.30 - 16.00 Claus Rolfs (EP3, Ruhr-Uni-Bochum, Bochum, Germany)
Electron-screening effects on fusion reactions

16.00 – 16.30 Coffee break

16.30 – ...... ROUND TABLE DISCUSSION: How to proceed ?
(Coordinator : S. Harissopulos, Workshop's convenor)

21-04-2002 SUNDAY

Departure

Abstracts
following the order in the programme

THE p-PROCESS: AN OVERVIEW

Marcel ARNOULD

Institut d'Astronomie et d'Astrophysique
Université Libre de Bruxelles, Brussels, Belgium

The p-process of stellar nucleosynthesis is aimed at explaining the production of the stable neutron-deficient nuclides heavier than iron that are observed in the solar system, and up to now in no other galactic location. Various scenarios have been proposed to account for the bulk p-nuclide content of the solar system, as well as for deviations ('anomalies') with respect to the bulk p-isotope composition of some elements discovered in primitive meteorites.

We set the stage of this exploratory workshop on the p-process by briefly reviewing some generalities concerning this mechanism of stellar synthesis, by pointing out some problems of special interest it raises, and by proposing a (non-exhaustive) list of open questions it still poses to both astrophysicists and nuclear physicists.

This review updates an earlier one that I have presented about 15 years ago at a very pleasant and fruitful workshop initiated by Themis Paradellis in a gorgious place in Crete. Before many others, Themis had already recognized at that time the interest the p-process might have for his experimental nuclear physics colleagues.

p process in type II supernovae

T. Rauscher
Department of Physics and Astronomy, University of Basel,
Klingelbergstr. 82, 4056 Basel, Switzerland

Stellar evolution of massive stars and explosive nucleosynthesis involve large reaction networks. Calculations for the evolution of Pop I stars of 15, 19, 20, 21, and 25 $M_\odot$ were performed, using the most recently available experimental and theoretical nuclear data, revised opacity tables, neutrino losses, and weak interaction rates, and taking into account mass loss due to stellar winds. A novel "adaptive" reaction network is employed with a variable number of nuclei (adjusted each time step) ranging from about 700 on the main sequence to more than 2200 during the explosion. The network includes, at any given time, all relevant isotopes from hydrogen through polonium (Z=84). This allows us for the first time to study the relevant nucleosynthesis processes - such as s-, n- and γ-processes - for these stars self-consistently within one network. In this presentation the focus is on the processes synthesizing the proton-rich p-nuclides. The production mechanisms are discussed as well as the sensitivity of our results on changes in the nuclear reaction rate sets. Theoretical approaches and nuclear properties important for the prediction of the involved rates are also addressed briefly.

The p process in type II Supernovae: current status

Vincenzo Costa

Osservatorio Astrofisico di Catania, Via S. Sofia 78, 95123 Catania, Italy

It is now considered plausible that the Neon-Oxygen layers of evolved massive stars ($M \geq 10 - 12\ M_\odot$) could be the main site for the synthesis of the p nuclei [1]. Nevertheless, there are problems connected with underproductions of p isotopes like $^{92,94}Mo$ and $^{96,98}Ru$. These problems might be cured by a correction of some uncertain key reaction rates strictly connected with the production of neutrons, within their level of uncertainty [2] [4]. One of these ($^{22}Ne(\alpha, n)^{25}Mg$) has been recently measured [3]. Implications of these new results and possible future perspectives are discussed.

[1] Rayet et al., 1995, Astronomy & Astrophysics 298, 517;

[2] Costa et al., 2000, Astronomy & Astrophysics 358, L67;

[3] Jaeger et al, 2001, Physical Review Letters vol.87, n.20;

[4] Angulo et al., 1999, Nuclear Physics A 656, 3.

New Reaction Rates of the Key Reactions of Stellar Nucleosynthesis: ^{12}C$(\alpha,\gamma)^{16}$O and ^{22}Ne$(\alpha,n)^{25}$Mg

J.W. Hammer[1], M. Jaeger[1], R. Kunz[1], M. Fey[1], A. Mayer[1], G. Staudt[2], S. Harissopulos[3], T. Paradellis[3] †, K.-L. Kratz[4], B. Pfeiffer[4]

[1] *Institut für Strahlenphysik, Univ. of Stuttgart, Germany*
[2] *Physikalisches Institut, Univ. of Tübingen, Germany*
[3] *Institute of Nuclear Physics, N.C.S.R. Demokritos Athens, Greece*
[4] *Institut für Kernchemie, Univ. of Mainz, Germany*

The excitation functions of the key reactions of stellar nucleosynthesis, ^{12}C$(\alpha,\gamma)^{16}$O and ^{22}Ne$(\alpha,n)^{25}$Mg, were determined with an experimental sensitivity of 10^{-11} barn. For ^{12}C$(\alpha,\gamma)^{16}$O the S_{E1}- and S_{E2}-factors deduced from the γ angular distributions have been extrapolated into the range of helium burning temperatures applying the R-matrix method, which yielded $S_{E1}^{300} = (76 \pm 20)$ keV b and $S_{E2}^{300} = (85 \pm 30)$ keV b. For the cascade transitions an upper limit of 8 keV b was obtained. To obtain an appropriate modeling of the extrapolation the separation of E1 and E2 capture was required.
In the case of ^{22}Ne$(\alpha,n)^{25}$Mg progress in sensitivity was obtained by the use of a new detector taylored to this specific reaction and the use of the gas target facility RHINOCEROS. Based on the new data, improved reaction rates were calculated as a function of temperature.
For ^{12}C$(\alpha,\gamma)^{16}$O the reaction rate at $T_9 = 0.2$ is $N_A\langle\sigma\, v\rangle = (7.9 \pm 2.5) \times 10^{-15}$ cm^3 (mol s)$^{-1}$ achieving a relative accuracy of $\pm\,30\,\%$. For ^{22}Ne$(\alpha,n)^{25}$Mg the reaction rate at $T_9 = 0.2$ is $N_A\langle\sigma\, v\rangle = (0.88\,^{+2.6}_{-0.3}) \times 10^{-16}$ cm^3 (mol s)$^{-1}$, improving the accuracy by about a factor of 100 compared to the recent NACRE compilation.

† deceased

Interferences between s- and p-Process Abundances

Franz Käppeler

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The observed abundances between Fe and the actinides exhibit contributions from neutron capture nucleosynthesis during stellar He-burning (s process) as well as from explosive nucleosynthesis in supernovae (r and p process). While the p components are usually small, they can account for a non-negligible fraction of some s-only isotopes. This interference is discussed in the light of the presently available cross section information, which has reached the accuracy for constraining the s-abundance patterns at the level of the p components.

On p-process related "anomalies" in meteorites

U. Ott

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Unlike (primarily) the s-process, no clear-cut stable isotope abundance anomalies that can clearly be related to p-process nucleosynthesis have been found in meteorites. Observed overabundances of p-isotopes generally are more likely due to s-process deficits (bulk analyses, pre-solar grains) or related to a specific type of p-process-like nucleosynthesis (pre-solar diamonds).

Clear indications, on the other hand, have been obtained for the presence in the early solar system of p-process radionuclides ^{146}Sm and ^{92}Zr. While currently some controversy exists as to the exact level of ^{92}Zr, the abundance level of ^{146}Sm is well established at $^{146}\mathrm{Sm}/^{144}\mathrm{Sm} \approx 10^{-2}$.

Extraction of level densities from primary γ-ray spectra

M. Guttormsen, J. Rekstad and S. Siem
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Box 1048 Blindern, N-0316 Oslo, Norway

A. Schiller
Lawrence Livermore National Laboratory, Livermore, CA-94551, USA

A. Voinov
Frank Laboratory of Neutron Physics, Joint Institute of Nuclear Research
141980 Dubna, Moscow reg., Russia

Important applications of nuclear level densities are the determination of nuclear reaction cross sections from Hauser-Feshbach type of calculations. These cross sections are used as input parameters in large network calculations of stellar evolution [1], and in the simulations of accelerator-driven transmutation of nuclear waste.

Unfortunately, the predictions of such calculations suffer from the lack of experimentally determined level densities. To day our knowledge is mainly based on the counting of discrete levels in the vicinity of the ground state and neutron resonance spacings at $6-8$ MeV of excitation energy.

Recently [2,3], the Oslo group has developed a technique to measure the level density from the ground state and up to the neutron binding energy. The method provides simultaneously the level density and gamma-ray strength function in one and the same experiment. In this group report we focus on the experimental technique and the underlying assumptions of the method. Thus, two crucial steps in the extraction procedure: (i) the subtraction technique for the primary gamma-ray spectra, and (ii) the Brink-Axel hypothesis, will be discussed.

The method has been successfully applied for rare earth nuclei where several thermodynamically properties, e.g. the pairing transition, have been investigated [4]. The future experimental effort will be concentrated on the $A = 30-100$ mass region, which play an important role in the nucleosynthesis of stellar objects.

1. T. Rauscher, F.-K. Thielemann and K.-L. Kratz, Phys. Rev. C **56**, 1613 (1997).
2. E. Melby et al., Phys. Rev. Lett. **83**, 3150 (1999).
3. A. Schiller et al., NIM **A447**, 494 (2000).
4. S. Siem et al., Phys. Rev. C **65**, 021306 (2002) and references therein.

Level densities and γ-strength functions: important quantities in nucleosynthesis

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Box 1048 Blindern, N-0316 Oslo, Norway

A. Schiller
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Frank Laboratory of Neutron Physics, Joint Institute of Nuclear Research
141980 Dubna, Moscow reg., Russia

Nuclear level densities and γ-strength functions are important nuclear properties which enter into nucleosynthesis models. Since the method [1,2] to experimentally extract these quantities will be discussed in detail in another talk by M. Guttormsen, this talk will focus on showing experimental results and how they compare to different theories with global parameterizations which often are used to model the level density and γ-strength function.

Neutron capture rates are commonly evaluated using the Hauser-Feshbach model and depend on the low-energy tail of the GDR which is the energy region we have been studying experimentally. We observe a pygmy resonance in the γ-strength functions of some of our nuclei. According to Ref. [3] a pygmy resonance in this region is an effect which "..can have a striking impact on the calculated r-abundance distribution". If a pygmy resonance can effect the (n,γ) rates it may also effect the (p,γ) rates, both important in the p-process of nucleosynthesis.

As nuclear physicists we study the level densities and γ-strength functions to learn more about the structure of the nucleus. We can therefor not resist the temptation to present some of our results [4,5] which show that these quantities can, in addition to be used in calculating reaction cross sections for nucleosynthesis models, also give other interesting information about the structure of the nucleus.

1. L. Henden, et al., Nucl. Phys. **A589**, 249 (1995).
2. A. Schiller et al., NIM **A447**, 494 (2000).
3. S. Goriely, Phys. Lett. **B 436**, 10 (1998).
4. E. Melby et al., Phys. Rev. Lett. **83**, 3150 (1999).
5. S. Siem et al., Phys. Rev. C **65**, 021306 (2002) and references therein.

Level densities far from the valley of stability

S. Hilaire
CEA/DAM IIe de France, DPTA/SPN, BP12, Bruyères-le-Châtel, France

Nuclear level densities play a crucial role in nuclear reaction calculations. When the excitation energy is above a few MeV, the number of levels is so large that it is impossible to track each of them individually. Consequently, the only tractable approach is statistical in nature and requires the use of level densities. Many theoretical and empirical studies have been performed during the last sixty years to provide either analytical expressions or numerical evaluations for both the particle-hole and total level densities. The main problem with the analytical approaches is that they depend on parameters which have to be adjusted to reproduce the available experimental data. Unfortunately the amount of such data is very limited. Indeed, among approximately 7000 nuclei predicted with a proton number $Z \leq 100$, experimental information useful for level density is available for only 300 of them. Moreover, these nuclei are very close to the valley of stability. It is therefore clear that the key parameters of analytical level density expressions can only be adjusted for nuclei close to the valley of stability, and the extrapolations that must be made to deal with nuclei far from this valley are rather risky.

To bypass such a limitation, the only possibility is to calculate theoretically the nuclear level densities to use them either directly in nuclear reactions calculations or to check the quality of the analytical extrapolations. As mentioned before, more or less complicated theoretical approaches can be employed for this purpose. All these methods have advantages and drawbacks, but since they are based on fundamental grounds, one can believe that they give more realistic results than simple extrapolated analytical expressions. Our goal is to show what are the main differences between what one can expect from simple extrapolated expressions and from theoretical approaches. We will also discuss the impact of using analytical or microscopic level densities on the cross sections relevant for nuclear processes involving nuclei far from the regions where the usually employed analytical expressions have been adjusted.

Improved global α optical model potentials for astrophysical applications

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Many nuclear astrophysics applications involve radiative α-particle captures, α decays and α-particle transfer reactions. Theoretical estimates of the corresponding reaction rates within the framework of the statistical model of Hauser-Feshbach remain highly uncertain due to the poor knowledge of the α-nucleus optical model potential, especially at low energies far below the Coulomb barrier. In the present paper we propose new global α-optical potentials that take into account the strong energy dependence and nuclear structure effects that characterize the alpha-nucleus interaction. The real part of the potential is calculated using a double-folding procedure over the M3KY effective nucleon-nucleon interaction. A Woods-Saxon potential is used for the imaginary potential where now a new parametrization is introduced to describe its energy dependence. Three potentials are developed, one with purely volume absorption, one with volume plus surface absorption, and finally, one where in addition to volume and surface absorption, the dispersive contributions obtained from the dispersive relation are included. The three potentials considered are able to reproduce the bulk of experimental data on (α,γ), (α,n), (α,p) and (n,α) reactions as well as the existing elastic scattering data at energies of relevance to astrophysical applications. However, when considering reaction rates for nuclei in the experimentally unexplored mass region, deviations within a factor of 10 are found. These uncertainties are mainly due to the difficulty in constraining the diffuseness of the imaginary potential from analyses of existing experimental data.

Photoneutron cross sections for the p-process

Hiroaki Utsunomiya

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Higashinada, Kobe 658-8501, Japan

Photonuclear reactions play an important role in nuclear astrophysics in two folds. They have direct impact on the nucleosynthesis of the p-process nuclei. The production and the destruction of the p-process nuclei through the (γ,n) reaction proceed in the low-energy tail of GDR. GDR cross sections and possible pigmy resonance near neutron threshold should be investigated with great accuracy.

The photonuclear reaction can also probe radiative-capture processes. For light nuclei with low level density, photonuclear reactions are inversely equivalent to radiative-capture processes with the ground state γ transition. For medium to heavy nuclei with high level density, partial photoneutron cross sections provide important information on neutron capture from low-lying excited states populated in a stellar photon bath.

I report the result of photoneutron cross section measurements on ^{181}Ta. Total cross sections were measured by direct neutron counting and partial cross sections leading to the ground state of ^{180}Ta (half-life = 8.152 h) were measured with an activation technique. The difference between the two ought to be the production cross sections of ^{180}Ta which is a long-lived p-process isomer with $J^{\pi} = 9^{-}$ at the excitation energy 75 keV. I also discuss a future research plan on the p-process and the s-process with quasi-monochromatic γ beams produced by inverse Compton scattering of laser photons from relativistic electrons.

Investigation of photon induced reactions during nucleosynthesis

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Institut für Kernphysik, Technische Universität Darmstadt,
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The production mechanism for the heavy (A≥100) p nuclei is photodisintegration in the γ process by successive (γ, n), (γ, p), and (γ, α) reactions [1]. For the calculation of the p nuclei abundances, large reaction networks containing all relevant nuclei and reaction rates are needed [2]. However, until now there has been almost no experimental data for these reaction rates in the relevant energy region.

We have started extensive experimental studies using an intense bremsstrahlung beam at the real photon set up [3] at the Darmstadt S–DALINAC accelerator in combination with the photoactivation technique. The relevant energy range is defined by a Gamow-like window which has a width of about 1 MeV starting from the neutron separation threshold for (γ, n) reactions at typical temperatures of T_9=2-3.

Two different methods are used to obtain the reaction rates: In the so called conventional method one assumes a structureless square root behaviour of the E1 cross section above the neutron threshold. The absolute value is fixed with a single cross section. In the superposition method the temperature dependent Planck spectrum is simulated via a superposition of various bremsstrahlung spectra. This method yields reaction rates without any assumption on the cross section [4,5].

First results on Pt-, Au-, Hg- and Pb-isotopes have been obtained and proof the high sensitivity of our set up [6]. It is shown that collective nuclear structure effects in the vicinity of the neutron threshold have a considerable impact on the reaction rates.

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(γ,α) reactions and α-nucleus potentials

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Photoreactions play a key role in the nucleosynthesis of heavy, neutron-deficient nuclei, the so-called *p*-nuclei, by a series of photon-induced reactions like (γ,n), (γ,p), and (γ,α) during supernova explosions at typical temperatures of about $T_9 \approx 2-3$ [1-3]. Nucleosynthesis calculations for this astrophysical process require extended reaction networks including more than 1 000 nuclei and 10 000 reactions; up to now they are mainly based on statistical model calculations, and practically no experimental data are available at astrophysically relevant energies.

It has turned out that predictions for (γ,α) reaction rates are very uncertain because they depend sensitively on the α-nucleus optical potential chosen. We have measured elastic scattering cross sections for ^{144}Sm(α,α)^{144}Sm [4] and ^{92}Mo(α,α)^{92}Mo [5] at energies close to the Coulomb barrier. From these experimental data one can derive the α-nucleus potential with small uncertainties. The obtained potentials fit nicely into the systematics of Refs. [6,7]. Because of the energy dependence of the α-nucleus potential, one has to extrapolate from the experimentally determined potentials at $E \approx 15-20$ MeV down to astrophysically relevant energies which are about $E \approx 5-12$ MeV. Whereas the real part of the potential is well-defined by the double-folding procedure, for the imaginary part the extrapolation remains uncertain.

The ^{144}Sm-α potential has been used for a prediction of the ^{148}Gd(γ,α)^{144}Sm and the inverse ^{144}Sm(α,γ)^{148}Gd cross section. Here experimental data are available down to about 10 MeV [8]. Especially at low energies significant discrepancies have been found which are related to the above mentioned uncertainties of the imaginary potential.

Recently, the potential systematics of Ref. [6] has been extended successfully to calculate various α-induced reaction cross sections at low energies [9]. A good agreement for the available data has been found, but nevertheless it has been stated that more precise experimental data are urgently needed to improve the predictive power of the calculations. Therefore, we plan new scattering experiments for several tin isotopes, and the extracted potentials have to be tested by predicting the respective (α,γ) cross sections, where experiments are under way [10].

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Experimental aspects of p-process studies using p- and α-beams

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Following the synthesis of p-nuclei and calculating their abundances requires an extended reaction network calculation involving more than 10 000 reactions mostly (γ,n), (γ,p) and (γ, α) photodisintegrations as well as (p,γ) and (α, γ) capture reactions. The results are strongly affected by the rates and therefore by the cross sections of these reactions. Low energy charged particle data are scarce in p-nuclei region (above iron), so the network calculations are based on purely theoretical data (Hauser-Feshbach statistical model). Therefore, a systematic experimental study of proton- and α-induced reaction cross sections was initiated in several institutions to put the calculations on a more reliable base. In the present work a list of the experimental works from the last 5-6 years is given and their results are compared to statistical model calculations.
Considerable differences to the theoretical predictions are found for α-capture reactions while the measured proton capture reactions exhibit less differences. The α-nucleus optical potential is the main source of the difference and this led to the idea of systematically studying elastic α-scatterings for getting experimentally determined potential parameters. These kind of experiments are also discussed in the present work.

Alpha and Neutron Induced Reactions on Ruthenium Isotopes

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The uncertain origin of the proton rich Mo and Ru isotopes has motivated cross section measurements of α- and neutron-induced reactions. The experiments were performed via the activation technique by irradiating thin layers of natural ruthenium with α-particle beams close to the Gamow window between 7.0 and 10.5 MeV. From the induced activities, the cross sections of the reactions ^{96}Ru(α,γ), ^{96}Ru(α,n), ^{96}Ru(α,p), and ^{98}Ru(α,n) could be determined with uncertainties of typically 10%. On average, these results are more than two times smaller than recent statistical model predictions. Additional activations in a quasi-stellar neutron spectrum corresponding to kT=25 keV allowed to obtain the complementary stellar (n,γ)-cross sections for ^{96}Ru, ^{102}Ru, and ^{104}Ru. In these cases the agreement with model calculations is considerably better.

(p,γ) and (p,n) cross sections in Se isotopes

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As continuation of a systematic study of the astrophysical p–process, an experimental investigation of (p,γ) or (p,n) cross sections of three Se isotopes has been carried out. Calculation of the abundances of the p–process nuclides requires extensive reaction network. An important input parameter for these network calculations is the reaction rate of various reactions obtained from the cross section. Very few cross sections involving light ions on relatively heavy nuclei, have been measured at energies appropriate to astrophysics, leaving these reaction networks dependent upon theoretical estimates of statistical models. The aim of our systematic study is to compare the experimental results with the predictions of statistical models and this way to check the reliability of the reaction network calculations for charged particle reactions and to put these calculations on a more firm base.

The experiments have been carried out at the 5 MV van de Graaff accelerator of the ATOMKI, Debrecen, Hungary. Activation method has been used to determine the cross section of the ^{74,76}Se(p,γ) and ^{82}Se(p,n) reactions in the proton energy range between 1.5 and 3.4 MeV with steps of 100 to 300 keV covering the relevant Gamow–peak which spans from 1.3 to 3.8 MeV.

Hauser-Feshbach statistical model calculations were carried out for the investigated reactions using the MOST code. The obtained cross section data have been compared with the experimental results.

Cross section measurements of the ^{78}Se(p,γ)^{79}Br and ^{80}Se(p,γ)^{81}Br reactions [1]

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In beam cross section measurements of the ^{78}Se(p,γ)^{79}Br and ^{80}Se(p,γ)^{81}Br reactions have been carried out at E_p=1.4-3.5 MeV, by using high efficiency HPGe detectors with BGO shields for Compton background suppression. A preliminary analysis yielded total cross sections ranging from 10 μb to 3 mb. By means of the statistical compound nucleus theory of Hauser-Feshbach cross sections have also been calculated. A comparison between experimental data and theoretical predictions is presented.

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(p,γ) cross sections of Sr isotopes [1]

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Cross section measurements of the proton capture reactions of the ^{86}Sr, ^{87}Sr and ^{88}Sr isotopes were carried out at energies E_p=1.4-5 MeV. At $E_p \leq 3.5$ MeV an array of 4 HPGe detectors with 100% relative efficiency shielded with BGO scintillators for Compton background suppression was used, whereas at $E_p \geq 3.5$ MeV, the measurements were performed by means of one HPGe detector of 80% relative efficiency. For the ^{87}Sr(p,γ)^{88}Y and ^{88}Sr(p,γ)^{89}Y reactions total cross sections ranging from 0.5 μb–5 mb were found. The data analysis of the ^{86}Sr(p,γ)^{87}Y reaction is in progress. Cross sections have also been calculated by means of the statistical model code MOST. A very good agreement between the experimental data and the theoretical predictions has been found.

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(p,γ) cross sections of ^{89}Y for astrophysical applications [1]

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The cross section of the ^{89}Y(p,γ)^{90}Zr reaction was determined at E_p=1.4-4.8 MeV via angle-integrated measurements carried out by means of a 4π NaI summing detector as well as via angular distribution measurements using an array of 4 HPGe detectors with 100% relative efficiency. The resulting cross sections vary from 0.5 to 5 mb. Astrophysical S factors and reaction rates have also been derived. A good agreement between the experimental rates and and the predictions of statistical theory has been found.

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Capture reactions relevant to p-process: present status and future needs

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During the last 5 years several cross section measurements mainly of proton capture reactions of nuclei in the Se-Sn region have been carried out in order to contribute to a database needed for calculations that are relevant to the modeling of p-process. Is the experimental information obtained so far sufficient for drowing some final conclusions? Are further measurements necessary? Is it really worth the experimental effort? In this contribution, several aspects of all experiments performed so far are commented and attempts to answers the questions mentioned above are presented for further discussion.

Electron-screening effects on fusion reactions

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It is in the nature of astrophysics that many of the processes and most of the objects one tries to understand are physically inaccessible. Thus, it is important that those aspects that can be studied in the laboratory be rather well understood. The electron screening effect on fusion reactions addresses one such aspect: the observed effect under laboratory conditions is presently not understood. This and some other challenging quests will be discussed.

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