Lecturers Abstract Book

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Big Bang and Stellar Nucleosynthesis, Plasmas in Stars and Laboratories, Neutron star mergers, Direct and Indirect Measurements, Detectors and Facilities for Nuclear Astrophysics, Experiments with RIB

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http://agenda.infn.it/event/astro2019

INFN Istituto Nazionale di Fisica Nucleare
Dipartimento di Fisica e Astronomia "Ettore Majorana"
ENSAR2
Centro Siciliano di Fisica Nucleare e di Struttura della Materia

Introduction to experimental nuclear astrophysics

F Hammache[1]

[1] *Institut de Physique Nucléaire d'Orsay, UMR8608, IN2P3-CNRS, Université Paris Sud 11, 91406 Orsay, France*

Our understanding of the various astrophysical nuclear processes responsible of the synthesis of the elements present in the Universe and stellar evolution has been largely improved thanks to the interaction between three fields: observation, stellar modeling and nuclear physics. All these fields are in constant development: new telescopes and satellites open more and more windows on the cosmos, stellar modeling relies on ever-increasing computing and nuclear physics takes advantage of new facilities (radioactive beams high-intensity beams, underground laboratories) and sophisticated detection systems.
Nuclear reaction rates are one of the most important ingredients in describing how stars evolve. The study of the nuclear reactions involved in different astrophysical sites is thus mandatory to address most questions in nuclear astrophysics. In the first part of the lecture, I will present some general features related to nuclear reaction cross-sections and thermonuclear reaction rates in stellar environments. In the second part, I will present the main characteristics of the reactions involved in quiscent burning phases and in explosive sites as well as the experimental challenges to measure their cross-sections. I will finish by giving an overview of the different experimental techniques used to determine these cross-sections.

Stellar evolution and standard solar model

S. Degl'Innocenti[1,2]

[1] *Physics Department Pisa University, Pisa, Italy*
[2] *INFN Pisa, Italy*

Star are gas masses at the hydrostatic and thermic equilibrium. During most of their life in their interior nuclear fusions are active producing energy which counterbalances radiative losses from the surface, stabilizing the star. The burning of different nuclear fuels during the star life, causes the time variation of the stellar characteristics, that is the "stellar evolution". The talk will discuss this topic focusing on the first evolutionary phases from the gravitational contraction with thermal timescale during the so called "Pre-Main Sequence phase" to the central H burning during the "Main Sequence phase" and the central H exaustion. The stellar characteristics in these evolutionary phases will be discussed. Finally the main features of the standard solar model will be described together with the solar neutrino production and its relevance to infer information on the solar interior.

Short introduction to the physics of neutron stars

I Vidana[1,2]

[1] *INFN - Sezione di Catania, Catania, Italy*
[2] *Dipartimento di Fisica e Astronomia, Universit degli Studi di Catania, Catania, Italy*

In this talk I shortly review several aspects of the physics of neutron stars. In particular, I review few aspects of their observation which include: the different types of telescopes that are used, the many astrophysical manifestations of these compact objects, and several observables such as masses, radii or gravitational waves. I go briefly also over some theoretical issues like their composition, structure equations, equation of state, neutrino emission and cooling processes.

Underground Nuclear Astrophysics: pushing direct measurements toward the Gamow window

P Prati[1]

[1] *Universitá di Genova, Genova, Italy*

The aim of experimental nuclear astrophysics is to provide information on the nuclear processes involved in astrophysical scenarios at the relevant energy range. However, the measurement of the cross section of nuclear reactions at the ow energies present formidable difficulties due to the very low reaction rates often overwhelmed by the background. Several approaches have been proposed and exploited to overcome such severe obstacle: in such frame, the idea to install a low energy - high intensity ion accelerator deep underground, to gain high luminosity while reducing the cosmic ray background, brought more than 25 years ago, to the pilot LUNA experiment. LUNA stands for Laboratory for Underground Nuclear Astrophysics: in the cave under the Gran Sasso mountain (in Italy) first a 50 kV and then a 400 kV single-ended accelerator for protons and alphas were deployed and produced plenty of data mainly on reactions of the H-burning phase in stars. Recently, similar facilities have been installed and/or proposed in other underground laboratories in US and China and LUNA as well is going to make a big step forward, with a new machine in the MV range and able to provide intense beams of protons, alphas and carbon ions. The rationale of underground nuclear astrophysics will be presented together the last updates on the ongoing research programs.

Recoil separators for nuclear astrophysics: the role of ERNA

L Gialanella[1,2]

[1] *Dipartimento di Matematica e Fisica, Universit della Campania, Caserta, Italy*
[2] *INFN - Sezione di Napoli, Napoli, Italt*

Proton and alpha particle radiative capture reactions are of utmost importance in nuclear astrophysics. Their direct study through gamma ray spectroscopy challenges experimentalists because of the low cross sections and the relatively high environmental background. Recoil mass separators (RMS) demonstrated to be a successful alternative approach in many cases, allowing a direct measurement of the reaction cross section by means of the direct detection of the nuclei produced in the reaction in a nearly background-free condition. In addition, the coincident detection of gamma rays allows investigating the partial amplitudes contributing to the total cross section. In this lecture the status and the perspectives in this field are reviewed taking the ERNA (European Recoil separator for Nuclear Astrophysics) RMS as an example.

Primordial Nucleosynthesis after Planck: Concordance, Discordance, and Dark Matters

B D Fields[1]

[1] *Department of Astronomy, University of Illinois, Illinois, USA*

We will survey the status of big-bang nucleosynthesis (BBN), which describes the production of the lightest nuclides during the first three minutes of cosmic time. We will emphasize the transformational influence of cosmic microwave background (CMB) experiments such as Planck, which pin down the cosmic baryon density to exquisite precision. Standard BBN combines this with the Standard Model of particle physics, and with nuclear cross section measurements, to make tight predictions for the primordial light element abundances. Deuterium observations agree spectacularly with these predictions, and helium observations are in good agreement. This CMB/BBN concordance marks a great success of the hot big bang, and BBN and the CMB together now sharply probe cosmology, neutrino physics, and dark matter physics at times around 1 second. But this success is tempered by lithium observations (in metal-poor halo stars) that are significantly discrepant with BBN+CMB predictions. We will review possible solutions to this "lithium problem" which could point to new stellar astrophysics, new nuclear physics, or new particle physics. Throughout we will highlight the continuing need for improved nuclear cross sections in order to keep pace with the ever-increasing precision of CMB and astronomical measurements.

Precision big bang nucleosynthesis with the new code *PRIMAT*

C. Pitrou[1,2], A. Coc[3], J.-Ph. Uzan[1,2], and E. Vangioni[1,2]

[1] *Institut d'Astrophysique de Paris, CNRS UMR 7095, 98bis Bd. Arago, 75014 Paris, France*
[2] *Sorbonne Université, Institut Lagrange de Paris, 98bis Bd. Arago, 75014 Paris, France*
[3] *Centre de Sciences Nucléaires et de Sciences de la Matière (CSNSM), CNRS IN2P3, Bât. 104, F-91405 Orsay Campus, France*

Precision on primordial abundances, deduced from observations, have now reached the percent level for ^{4}He and deuterium. Precision on BBN predictions should, hence, reach the same level.

In the case of deuterium, it is mostly governed by precision on experimental cross sections[1]. On the contrary, even though the uncertainty on the ^{4}He mass fraction comes partially from the experimental neutron lifetime, it was also strongly affected by theoretical uncertainties on the weak reaction rates that interconvert neutrons with protons. For these rates, the radiative, finite nucleon mass, finite temperature radiative corrections, weak-magnetism, QED plasma effects, and consequences of incomplete neutrino decoupling have all been calculated for the first time in a self-consistent manner[2]. For all of them, detailed balance was enforced, an essential requirement as there rates govern the n/p ratio at freeze-out and, consequently the ^{4}He abundance.

Even if they are small, these corrections affect the predictions by 1.84% for ^{4}He and 1.49% for deuterium, larger that the observational uncertainties. Hence, they are essential, not only for ^{4}He abundance prediction but also for the deuterium one.

These predictions were obtained with a new BBN Mathematica code *PRIMAT*, developed and made publicly available[3]. Its network of 391 reactions and 59 beta-decay processes allows to predict abundances up to the CNO region with the most up to date nuclear input. It can be freely modified to incorporate new physics, or simply modify the nuclear network. Examples will be given on how to include new reactions or update reaction rates.

This Mathematica code evolved from the Fortran code *EZ_BBN* [1], in which the corrections to the weak rates, listed above, are in the process of, also, being implemented. At present the main corrections are included in a version of the Fortran code, coupled with a small network, but giving results (for ^{4}He, D, ^{3}He, and ^{7}Li only) close to the more sophisticated *PRIMAT*. This version can be shared with the students of the School, before the more extended Fortran version is available.

[1] A. Coc & E. Vangioni, International Journal of Modern Physics E, 26, (2017) 1741002, arXiv:1707.01004 [astro-ph.CO]
[2] C. Pitrou, A. Coc, J.–P. Uzan & E. Vangioni, Phys. Rep. 754 (2018) 1-66, arXiv:1801.08023
[3] http://www2.iap.fr/users/pitrou/primat.htm

Connections Between Nuclear Physics and the Origin of Life

M Famiano[1]

[1] *Department of Physics, Western Michigan University, USA*

The discovery of bio-molecules in meteorites with an excess of one chiral state has created one of the biggest questions in science today. That is, what is the origin of bio-molecular homochirality? Studies of this question are highly interdisciplinary, and while several pheonomenological models exist, we examine the relationship between fundamental symmetries at the particle level and the macroscopic formation of bio-molecules. A model has been developed which couples fundamental interactions with the formation of molecular chirality. In this magneto-chiral model atomic nuclei bound in amino acids interact via the weak interaction in stellar environments. Nuclei are coupled to the molecular geometry (chirality) via the shielding tensor the same interaction responsible for NMR identification. Associated with this is the fact the isotopic abundances vary from solar system values. Interactions with leptons can then selectively destroy one chiral state over the other while changing isotopic values. Possible sites are proposed in which this model may exist.

It may be possible to test the formation of chiral bio-molecules in space in an electron beam experiment at a facility much like the one at several worldwide facilities. Such an experiment will be discussed along with several problems and questions associated with it.

[1] M. Merlin et al., Int. J. of Magic **615**, 934 (2004).

Heavy Element Synthesis under Explosive Burning on Neutron Stars

Shigeru KUBONO[1,2]

[1] *RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
[2] *Center for Nuclear Study, the University of Tokyo, RIKEN capus, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*

Nucleosynthesis under explosive nuclear burning conditions is of great interest for heavy element production both for neutron-rich and proton-rich nuclides. Specifically, a binary system that involve neutron stars has such environment, and is considered to be an interesting and exciting subject for nuclear astrophysic. Type I X-ray burst takes place on a neutron star in a binary system with a main sequence star by having acretion of hydrogen gas from the accomanying star. The thermonuclear run away, drived by the rp-process, induces the X-ray bursts. A recent X-ray observation[1] suggests that the rp-process runs up to the nuclei of Z=48 - 49. However, there are a few, possible waiting points and bottle necks[2] before reaching the endpoint. Recent experimental efforts will be discussed for this problem.

Another interesting subject of explosive burning is the r-process in the bi neutron star merger. The kilo nova, the after glow due to nuclear decays of the r-process nuclides, was successfully obsered right after the gravitational wave detection of GW170817[3]. Many optical telescopes have observed the glow decaying rapidly after the merger together with a color change from blue to red in about ten days[4]. Although the observations were not sensitive to identify the elements produced in this event, possible radio activities were identidied.

I will discuss this subject and identify the possible problems to be inestigated both in nuclear physics as well as in observation.

[1] M. Kubota et al., Publ. Astron. Soc. Japan (2019) 1.
[2] For instance, H. Suzkuki, et al., Phys. Rev. Lett. 119 (2017) 192503.
[3] B.P. Abott, et al., Phys. Rev. Lett. 119 (2017) 161101.
[4] S.J. Smartt, et al., Nature 551 (2017) 75.

RIB: production and experiments

M Mazzocco[1]

[1] *Department of Physics and Astronomy, Universitá degli Studi di Padova, Padova, Italy*

Radioactive nuclei are involved in several reactions of astrophysical interest in the entire evolution of our universe, from the Big-Bang Nucleosynthesis to the catastrophic explosive scenarios of massive stars. Major facilities for the Radioactive Ion Beam (RIB) production have been under construction worldwide. The RIB production scheme mainly makes use of two alternative techiniques: In-Flight (IF) and Isotope-Separation-On-Line (ISOL). The main features of both techiques, together with the related positive aspects and possible drawbacks, will be reviewed. As an application, the RIB production at the In-Flight facility EXOTIC, located at the Laboratory Nazionali di Legnaro, will be described and the results of the most recent experiments will be presented.

Electron screening in nuclear reactions

M. Lipoglavsek

Jozef Stefan Institute, Ljubljana, Slovenia

Electron screening influences nuclear reactions at low energies. This is important in astrophysical scenarios from primordial to stellar nucleosynthesis. The classical model of electron screening [1], where electrons are placed on a sphere with the atomic radius, could not be confirmed by experiments. Namely, most laboratory experiments show a significantly larger electron screening effect than predicted by the theory. I will overview the experimental results, including our latest results on deuterated titanium targets. We have recently succeeded in reproducing the large measured electron screening potentials by solving on a lattice the Schrödinger equation for a single electron in the attractive potential of the two approaching nuclei.

[1] H. J. Assenbaum, K. Langanke and C. Rolfs, Z. Phys. **A327**, 461 (1987).

Nuclear Physics Using Lasers

A Bonasera[1,2]

[1] *Cyclotron Institute, Texas A&M University, College Station, TX-77843, USA;*
[2] *Laboratori Nazionali del Sud, INFN, via Santa Sofia, 62, 95123 Catania, Italy (on leave).*

The plasma astrophysical S factor for the 3He(d,p)4He fusion reaction was measured for the first time at temperatures of few KeV, using the interaction of intense ultrafast laser pulses with molecular deuterium clusters mixed with 3He atoms. The experiments were performed at the Petawatt laser facility, University of Texas, Austin-USA. Different proportions of D2 and 3He or CD4 and 3He were mixed in the gas target in order to allow the measurement of the cross section. The yield of 14.7 MeV protons from the 3He(d,p)4He reaction was measured in order to extract the astrophysical S factor at low energies. Recent results obtained at the SGII-laser facility, Shanghai-China on the CD2 targets will be discussed with particular emphasis on the reached high densities. Hydro-dynamical calculations will be presented for some experimental situations and the limits of the model will be stressed. Some simulations for possible experiments at ELIMED will also be presented. [1] [2] [3] [4] [5] [6] [7] [8]

[1] PRL 111, 082502 (2013);PRL 111, 055002 (2013)
[2] PHYS.REV. E 88, 033108 (2013)
[3] NIM A 720 (2013) 149152
[4] Progr.Theor.Phys. Supplement No. 154, 2004, 261
[5] http://physics.aps.org/synopsis-for/10.1103/PhysRevLett.111.082502
[6] PLA383(2019)2285
[7] PLA381(2017)1682
[8] PLA382(2018)94

^{8}Be: Confronting ab-initio Nuclear Theory and Data on Big Bang Nucleosynthesis

Moshe Gai[1]

[1] *University of Connecticut, USA*

The interaction of neutrons with 7Be that was measured at the SARAF in Israel with a quasi-Maxwellian neutron beam at 49.5 keV reveals a strong B(E1: 2- $\rightarrow$ 2+) $\tilde{0}$.04 W.u., decay of the 2- state at 18.91 MeV in 8Be to the alpha-cluster 2+ state at 3.03 MeV [1]. This strong E1 decay leads to large cross section of the 7Be(n,γ_1)8Be(3.03) reaction at the "BBN window". It implies s-waves dominance of the cross section at the "BBN window", in contrast to previous extrapolations into the "BBN window" from lower energies (the n_TOF measurement [2]) and extrapolation from higher energies into the BBN window (the Kyoto measurement [3]).

In addition, the phenomenological structure of all states below 19.5 MeV in 8Be (including the 2- state at 18.91MeV) provides good evidence for particle-hole (p-h) states in the newly proposed Cluster Shell Model (CSM) of Della Roca and Iachello [4]. The states near the neutron and proton thresholds in 8Be show the characteristic of the p-h states predicted by the CSM. The measured B(E1) of the 2- state at 18.91 MeV is in accordance with other measured decays of the p-h CSM states to the well-known cluster ground-state and 2+ state at 3.03 MeV in 8Be. The new CSM model of Della Roca and Iachello [4] will be introduced with emphasize on the similarity between p-h states in 8Be and single particle states in 9Be.

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[1] M. Gai, arXiv:1812.09914v1, (2018).
[2] M. Barbagallo et al., Phys. Rev. Lett. 117, 152701 (2016).
[3] T. Kawabata et al., Phys. Rev. Lett., 118, 052701 (2017).
[4] V. Della Rocca and F. Iachello, Nuclear Physics A 973, 1 (2018).

Neutron Skins, Symmetry Energy, and Neutron Stars

C.A. Bertulani[1]

[1] *Department of Physics and Astronomy, Texas A&M University-Commerce, Texas 75429, USA*

I will present a brief overview on the quest to determine the Equation of State (EoS) of neutron stars. Early experimental studies of pygmy resonances in neutron-rich nuclei will be discussed together with theoretical attempts to develop relationships between the properties of pygmy resonances and the EoS of neutron stars. Recent efforts to correlate neutron skins in nuclei and the EoS will also be presented. Focus will be given to microscopic descriptions of nuclei, how they predict diverse EoS, and how one can constrain their predictions by comparison with experiments at nuclear facilities and with astronomical observations [1-5].

[1] C.A. Bertulani, arXiv:1904.10628 (2019).
[2] Shubhchintak, C.A. Bertulani and T. Aumann, Phys. Lett. B 778, 30 (2018).
[3] T. Aumann, C.A. Bertulani, F. Schindler, S. Typel, Phys. Rev. Lett. 119, 262501 (2017).
[4] C.A. Bertulani and T. Kajino, Prog. Part. Nucl. Phys. 89, 56 (2016).
[5] V. Gates, Empty Kangaroo, M. Roachcock, and W.C. Gall, Physica D: Nonlinear Phenomena 15, 289 (1985).

Experimental Nuclear Astrophysics: THM for Resonant Reactions

M La Cognata[1]

[1] *Laboratori Nazionali del Sud, INFN, Catania, Italy*

Resonance reactions play a very important role in astrophysics as resonances may dramatically change cross sections of relevant reactions at low energies. Since astrophysical energies can be as low as 10-100 keV during quiescent burning, they can be hardly achieved with standard approaches and astrophysical models usually rely on extrapolations. However, at these energies the effect of atomic electrons cannot be neglected, also determining an increase of the astrophysical factor at low energies, resembling the effect of a sub threshold resonance, for instance. The Trojan Horse Method (THM) has proved very useful to measure cross sections at very low energies, allowing us to reduce systematic uncertainties associated with the extrapolation procedure. It has been modified to investigate resonance reactions, both in the case of low energy resonances and of sub threshold resonances. This upgrade of the THM is based on the modified R-matrix approach, accounting for the off-energy-shell nature of the transferred particle. In the case of sub threshold resonances, it has been possible to extract the asymptotic normalisation coefficient, with important consequences in the development of indirect methods. We will show some recent results, about the 19F(p,a)16O and 13C(a,n)16O reactions to illustrate the resonance THM for two important astrophysical processes, with possible consequence on fluorine and s-process nucleosynthesis. We will expose a step-by-step approach showing the application of the THM, from the experiment to the astrophysical factor and the discussion of the astrophysical consequences. Also, the link with other indirect techniques, the asymptotic normalisation coefficient (ANC) and the Coulomb dissociation (CD), will be shown, demonstrating the cross-links and the further developments of the method.

Transfer reactions for nuclear astrophysics

N De Sereville[1]

[1] *Institut de Physique Nucleaire d'Orsay, Orsay, France*

One of the main ingredient in nuclear astrophysics are thermouclear reaction rates which depend on the cross-section between the interacting species. These cross-sections are extremely small at astrophysical energies and their determination is a major experimental challenge. Though direct measurements are feasible in some cases, and should be prefered when possible, indirect methods are sometimes the only way to determine contribution of low-lying/subthreshold resonances to the cross-section. They are also often the unique way to determine the cross-section when radioactive species are involved.

In this lecture I will focus on transfer reactions which are one of the many indirect methods available. In a first part I will introduce the transfer reaction method: what are the observables, what spectroscopic information can be extracted, and how the Distorted Wave Born Approximation can be used to describe theoretically such kind of reactions. In the second part of the lecture I will present a few recent experimental works involving stable and radioactive beams, and a variety of experimental setups.

Coulomb dissociation method for radiative capture of astrophysical interest

T Motobayashi [1]

[1] *RIKEN Nishina Center, Japan*

The dissociation process induced by virtual photons created in a strong Coulomb field provides several interesting cases of nuclear physics studies. If influence of the nuclear interaction is negligible or well under control, the Coulomb dissociation cross section can be converted to the one for the corresponding photo absorption process. For example, the strength of electric dipole excitations, which is usually studied by photon induced reactions, can alternatively be determined by Coulomb excitation or dissociation experiments. This is useful especially for the cases involving unstable nuclei that cannot be served as targets. Thanks to recent developments of fast RI (radioactive isotope) beam production, access to such cases becomes possible by employing so called inverse kinematics. For instance, The halo nature of the neutron rich 11Be nucleus was confirmed by measuring its electric dipole response by Coulomb dissociation. A lot of studies of Coulomb excitation of unstable nuclei have been performed. An advantage of the Coulomb dissociation or excitation is in the capability of relating the cross section to the photo absorption cross section, as mentioned, or the electric transition probability, because the intensity of the virtual photons can be obtained through an appropriate reaction theory.

The Coulomb dissociation has also been applied to radiative capture reactions of astrophysical interest. In nucleosynthesis in stars or in the early universe, (p,γ), (n,γ) and other radiative capture processes play very important roles. Since these processes are inverse of photodisintegration process that can be studied by the Coulomb dissociation as already discussed. Especially for studying explosive nucleosynthesis involving short lived nuclei, experiments in inverse kinematics with RI beam provide unique opportunities. The lecture will discuss about this Coulomb dissociation method with some examples of experiments at RIKEN RI Beam Factory.

Stellar evolution for massive stars

A Chieffi[1]

[1] *Istituto di Astrofisica e Planetologia Spaziale - INAF, Roma, Italy*

In my talk I will start by showing that we can learn many things about the evolution of the stars by means of a simple analysis of the equations that control their structure and evolution. Then I will discuss the key problems connected with main evolutionary phases: H, He, C, Ne, O burning, approach to the NSE and final collapse. I will also briefly discuss the role of rotation and initial metallicity on the evolution of a massive star.

Explosive Nucleosynthesis in Core Collapse Supernovae

M Limongi[1]

[1] *Osservatorio Astronomico di Roma - INAF, Roma, Italy*

Core Collapse Supernovae are the endpoint of the evolution of massive stars (M ¿ 10 M_{sun}). They play a fundamental role in the evolution of the Universe because, among the other things, contribute to the production of most of the elements (especially those necessary to life), induce star formation when the shock wave following the explosion passes though the interstellar medium, produce neutron stars and black holes, are connected to the GRB events (some of them) and last, but not least, are one of the sources of gravitational waves. Therefore, a good knowledge of these events are needed to shed light on many astrophysical topical subjects. In this lecture I will mainly focus on the role of core collapse supernovae in the chemical evolution of the matter and, in particular, on the nucleosynthesis occurring during the explosion. I will describe the basic principles of the nuclear burning at high temperatures coupled to the dynamics of the exploding mantle of the star and will show the main products of the various explosive burning. For sake of completeness I will also briefly discuss the chemical composition of the final ejecta, how it depends on the progenitor star and on the remnant mass. Finally, I will show which is the contribution of a generation of massive stars (i.e., core collapse supernovae) to the global enrichment of the interstellar medium.

Asyntotic Giant Branch Stars and Pre-solar Grains

M. Busso[1,2]

[1] *Department of Physics and Geology, University of Perugia, Italy*
[2] *INFN Section of Perugia, Italy*

I outline the role played in the last decades by the analysis of the composition of pristine meteorites in providing constraints to the nucleosynthesis of rare nuclei by low and intermediate mass Asymptotic Giant Branch (AGB) stars. Starting from the recognition that live radioactive isotopes were present alive in the Early Solar System, derived from the identification of their daughter nuclei in the composition of bulk meteorites and in Ca-Al inclusions, and through the discovery that important anomalies affected also stable species, I shall mention how the carriers of these anomalous concentrations were realized to be very refractory pre-solar dust grains, formed in the circumstellar environments of various types of stars. I shall then discuss how the refinement of the techniques permitted to separate and analyze firstly groups of such grains and subsequently single crystals of C-rich or O-rich materials (like, e.g., SiC, Al_2O_3, etc.), thus providing a very effective tool to measure the composition of the solid component of stellar winds. As AGB stars are the primary source of dust in the Galaxy, they also dominate the scene in producing pre-solar grains recovered from meteorites, so that these last now offer a crucial window on the details of nucleosynthesis processes, especially for slow neutron captures (the s-process) occurring in the final evolutionary stages of moderately massive stars.

The activation method for cross section measurements in nuclear astrophysics

Zs Fülöp[1]

[1] *MTA Atomki, Debrecen, Hungary*

The activation method is presented in the context of nuclear astrophysics as a useful tool to determine cross sections of nuclear reactions relevant to nuclear astrophysics [1]. Using the method cross sections can be determined based on off-line detection of the decay of residual isotopes. The activation method can be used successfully if the final nucleus of an astrophysically important reaction is radioactive with an adequate half-life and branching ratio. This method, while having serious limitations, in some cases also can have substantial advantages over the in-beam particle- or γ-detection measurements. Charged particle induced reactions relevant to the astrophysical p-process will be presented as examples. The extension of activation technique with X-ray detection will be presented as a tool to increase the sensitivity of activation experiments.

[1] Gy. Gyürky, Zs. Fülöp, F. Käppeler, G.G. Kiss, A. Wallner, Eur. Phys. J. **A55**, 41 (2019).

Neutrino-induced Nucleosynthesis

Taka Kajino[1,2]

[1] *NAOJ & The University of Tokyo (Japan)*
[2] *Beihang University (P.R. China)*

Gravitational wave radiation associated with gamma-ray, X-ray, and optical-infrared light emission from GW170817/SSS17a was the event of the centuries that opened a new window to multi-messenger astronomy. The nuclear astrophysics today in multi-messenger era stands on new stage of understanding the origin of elements from interdisciplinary aspects that cross over the nuclear physics, neutrino physics, astronomy and astrophysics, and even cosmology. I will lecture the fundamentals of these physics with special emphasis on neutrinos. Then, we will first discuss a long-standing problem of overproduction of primordial 7Li, which is affected by the neutrino interactions and primordial magnetic field (PMF). Much efforts have ever been made to measure the precise nuclear reaction cross sections relevant for BBN, which does not seem to solve the problem. We challenge this problem by taking account of the PMF which is consistent with CMB anisotropy [1]. This effect mimics non-Maxwellian energy distribution called Tsallis statistics that affects nuclear reactions as reported in [2]. The second topic is the similarity and difference between BBN and stellar and supernova nucleosynthesis for those of 60¡A. The roles of light-to-heavy mass nuclear reactions in the solar neutrino problem and r-process nucleosynthesis will be discussed. The initial condition of either SN or merger r-process depends on neutrino-nucleon interactions. Neutron star merger and supernova are the most viable candidates for the r-process [3,4]. The essential difference between these two explosive phenomena is the emergent event rate as a function of cosmic time in addition to the difference in nucleosynthesis. SNe can explode in a few My from the early Galaxy, while mergers rarely happen at the rate of ¡1% of SN rate and delay by $\sim$100 My due to very slow GW radiation. We will discuss cosmic evolution of r-process elements by taking account of SNe and mergers [5,6]. The third topic is the neutrino oscillations in SNe. The elements with mass A¡100 originate from many processes such as rp-, γ-, ν-, νp-, s-, and r-processes [7]. The p-process (i.e. ν-induced proton process) operates strongly when free neutrons are supplied via p(ν,e+)n reactions by taking account of the effects of collective neutrino oscillations [8]. The p-process produces abundant p-nuclei like 94Mo, 96Ru, etc. This nucleosynthetic method turns out to be a unique probe indicating still unknown neutrino-mass hierarchy. Finally, we will also discuss how to constrain neutrino-mass hierarchy by predicting the energy spectrum of diffusive Galactic supernova neutrinos to be detected by SK or HK in the near future [9].

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In beam cross section measurements of capture reactions relevant to p-process: the nuclear astrophysics program of the CALIBRA project*

S V Harissopulos[1]

[1] *Tandem Accelerator Laboratory, Inst. of Nuclear and Particle Physics, NCSR Demokritos, Athens, Greece*

Stellar nucleosynthesis of heavy elements up to the Fe-Ni region are produced in cosmos primarily by charged-particle thermonuclear reactions. When reaching Fe, the Coulomb barrier becomes the highest, making any attempt to proceed to heavier masses by means of charged-particle induced reactions almost impossible. To overcome this problem, nature employs neutrons to be captured by already formed nuclides, which then may decay by emitting electrons (βdecay). As a result, the vast majority of the stable nuclei heavier than Fe are produced with the s process and to lesser extend with the r process. However, among the stable nuclei that are heavier than iron there exist 35 nuclei which lie "north-west" of the stability valley between 74Se and 196Hg. These nuclides, known as p nuclei, cannot be synthesized by either the s or the r process because stable isobars shield them from the decay of more neutron-rich nuclei. To date, p nuclei have been observed only in the solar system and the prediction of the solar-system abundances of the p nuclei is one of the major puzzles of all models of p-process nucleosynthesis, with some striking cases, like 92Mo. Until now all p-process nucleosynthesis models are capable of reproducing these abundances within a factor of 3, however, they all fail in the case of some light p-nuclei with A$\sim$100 and a few heavier ones. Although, these discrepancies could be attributed to uncertainties in the pure astrophysical modelling, nuclear physics uncertainties also need to be considered. This is because astrophysical abundance calculations make an extensive use of the nuclear statistical model to obtain a vast number of cross sections that are necessary for the calculation of the reaction rates of an extended reaction network of more than 20000 reactions involving almost 2000 nuclei heavier than iron. It is hereby worth noting that the vast majority of these reactions involves unstable target nuclei far off stability that are hardly reachable, even with the latest developments in the production and acceleration of radioactive (unstable) ion beams. It is therefore of paramount importance, on top of any astrophysical model improvements, to test also the reliability of the statistical model calculations, i.e. to investigate the uncertainties associated with the evaluation of the nuclear properties entering the Hauser-Feshbach (HF) calculations. Among these properties, the nuclear level densities (NLDs) and the nucleon-nucleus and, especially, the -particle-nucleus optical model potentials (OMPs) were found to have the strongest contribution to the uncertainties in the HF calculations. It is worth mentioning that the HF predictions obtained by using different -OMPs lead to differences in the cross sections up to a few orders of magnitude. This problem is certainly propagated in the modelling of the p process. To test the predictive power and the global character of the existing nucleon-nucleus and -particle-nucleus potentials is of primary importance to measure cross-sections of certain (p,γ) and (α,γ) reactions and furthermore establish an extended cross-section database for capture reactions covering a wide mass range. Up to date, considerable effort has been devoted to improve our knowledge of the behavior of the -nucleus OMP at energies relevant to p-process. Recently, the 4π γ-summing method was developed by the groups of "Demokritos" and Bochum. Using this new method, cross sections of more than 20 (p,γ) and (α,γ) reactions were determined at energies within the Gamow window. In this presentation, a review of recent experimental and theoretical developments will be communicated. Hereby, capture reaction cross-sections will be compared with the predictions of the statistical model. Finally, the question of whether there is sufficient experimental information to put constraints on the theory and draw final conclusions will be discussed.

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Nucleosynthesis of light trans-Fe r-, p- and s-isotopes: Implications from presolar SiC X-grains

K-L Kratz[1], W Akram[2], K Farouqi[1], O Hallmann[1,3]

[1] *Faculty of Chemistry, Pharmaceutical Sciences, Geography and Geosciences, Johannes-Gutenberg University of Mainz, D-55128 Mainz, Germany*
[2] *Department of Earth Sciences, University of Oxford, Oxford OX1 3AN, UK*
[3] *Max-Planck-Institute for Chemistry (Otto-Hahn-Institute), D-55128 Mainz, Germany*

In the present contribution, we report on an extension of our r-process parameter study within the high-entropy-wind (HEW) scenario of core-collapse supernovae (ccSNe) [1-3]. One of the primary aims of this study was to obtain indications for the co-production of classical r-, p- and s-isotopes of the light trans-Fe elements in the Solar System (S.S.) [4, 5].

Here, we focus on the possible nucleosynthesis origin of the peculiar isotopic compositions of Zr, Mo and Ru in presolar SiC X-grains discovered by the Argonne group [6]. In contrast to the interpretation of other groups, we show that these meteoritic observations do not represent the signatures of a 'clean' stellar scenario, but rather are mixtures of an exotic nucleosynthesis component with S.S. material.

We furthermore confirm the results of our earlier studies [4] whereby sizeable amounts of all stable r-, p- and s-isotopes of Zr, Mo, and Ru can be co-produced by moderately neutron-rich ejecta of the low-entropy, charged-particle scenario of Type II ccSNe. The synthesis of these isotopes through a 'primary' production mode provides further means to revise the abundance estimates of the light trans-Fe elements from so far favored 'secondary' scenarios like Type Ia SNe (see, e.g. [7]) or neutron-bursts in exploding massive stars (see, e.g. [8, 9]).

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Star Formation under Cosmological Conditions

M F El Eid[1]

[1] *American Univ. of Beirut, Dept. of physics, Beirut, Lebanon*

The first stars have transformed the Universe from darkness into light, thereby ending the Dark Age via re-ionization by their UV-light. An overview will be given about the cosmological connection of the first star formation in the universe. The physical background underlaying the process of their formation is discussed. Their Basic properties will be described, and some results of numerical simulations are presented.

Achievements and perspectives of the Gravitational wave astronomy - Einstein Telescope

M Punturo[1]

[1] *INFN - Sezione di Perugia, Perugia, Italy*

In the last few years, Advanced LIGO and Advanced Virgo opened the era of the gravitational wave astronomy and of the multi-messenger astronomy with gravitational waves. A series of achievements in physics, astronomy and cosmology demonstrated the awesome scientific potential of this sector of research, boosting the activities of designing and realisation of the next generation of gravitational wave observatories. The cornerstone scientific results of the current gravitational wave detectors and the perspectives of the 3rd generation gravitational wave observatory, Einstein Telescope, will be presented.

r-Process nucleosynthesis in realistic astrophysical scenario

Nobuya Nishimura[1]

Center for Gravitational Physics, Yukawa Institute for Theoretical Physics, Japan

The understanding of r-process nucleosynthesis, based on astronomical observation, has been growing in recent years. There are several observational constraints (e.g., the abundances of metal-poor stars and a kilonova with GW170817) on the nucleosynthesis process, which is occurred in very neutron-rich conditions of explosive astrophysical phenomena. For the complete understanding of the r-process, however, we should know more details of the mechanism of core-collapse supernovae and neutron-star mergers. Besides the astrophysical aspects, we are required to understand the physical properties of neutron-rich nuclei, of which decay and reaction properties are still unknown.

In this talk, I will review the recent progress of astrophysical sites, mainly focusing on neutron-star mergers. I emphasize that neutron-star mergers have the multiple components of ejecta which has different neutron-richness, which result in from the "weak" r-process to the "strong" r-process. Then, I discuss the possibility of alternative r-process sites, i.e., magneto-rotational-driven (jet) supernovae, which can be dominant sources of r-process elements in early galaxies. Based on the discussion on the astrophysical conditions, I also briefly remark the impacts of nuclear-physics inputs on the r-process calculations used in the astrophysical studies.

Nuclear astrophysicsactivities at the n_TOF facility at CERN

A Mengoni[1]

[1]*ENEA Bologna and INFN, Sezione di Bologna, Italy*

Neutron induced reactions play an important role amongst the many facets of the research activities in nuclear astrophysics: from big-bang to stellar nucleosynthesis, from galactic chemical evolution to nuclear cosmo-chronometry. An extensive experimental program of neutron induced reaction cross section measurements for applications to nuclear astrophysics, advanced nuclear technologies and basic nuclear sciences has been planned and executed at the CERN neutron time-of-flight facility n_TOF during the course of the last twenty years. A few, selected, examples of this program will be presented which includes measurements and theoretical interpretation of the neutron capture cross sections for the Re/Os clock, neutron to charged-particle reactions for big-bang nucleosynthesis (such as (n,a) and (n,p) on Be-7), reactions and nuclear spectroscopy for the s-process neutron sources.

SN from observation perspective

M della Valle[1]

[1] *Osservatorio di Capodimonte - INAF, Napoli, Italy*

I'll review the main observational facts of Supernovae and their impact on topics of modern Astrophysics, such as Cosmology and search for the optical counterpart of Gravitational Waves.

ANC experiments for nuclear astrophysics

G.D'Agata[1], V.Burjan[1], J.Mrazek[1], V.Glagolev[1], A.I.Kilic[1], V.Kroha[1], M.La Cognata[2], L.Lamia[2,3], S.Palmerini[4,5], S.Piškor[1], R.G. Pizzone[2], G.G.Rapisarda[2], S.Romano[2,3] I.Siváček[1], R.Spartá[2], C.Spitaleri[2],A.Tumino[2,6]

[1] *Nuclear Physics Institute of the Czech Academy of Sciences, 250 68 Řež, Czech Republic*
[2] *INFN - Laboratori Nazionali del Sud, Via Santa Sofia 62, 95123, Catania, Italy*
[3] *Dipartimento di Fisica e Astronomia, Università degli Studi di Catania, Via Santa Sofia 64, 95123, Catania, Italy*
[4] *Dipartimento di Fisica e Geologia, Università degli Studi di Perugia, via A. Pascoli s/n, 06123, Perugia, Italy*
[5] *INFN-sezione di Perugia, via A. Pascoli s/n, 06123, Perugia, Italy*
[6] *Facoltà di Ingegneria ed Architettura, Kore University, Viale delle Olimpiadi, 1, I-94100 Enna, Italy*

Experimental measures on relevant reactions for astrophysics have proven to be a challenge: the presence of the Coulomb barrier between charged particles, in fact, highly decreases the cross-section in the energy range (from few keV to some MeV) of interest. Therefore, it is not easy to explore such reactions with direct methods, and many indirect ones were developed. One of the most widely used consists in retrieving the so-called Asymptotic Normalization Coefficient (ANC) of the overlap function for the bound-state wave functions in the initial and final states[1,2]. This method is used under the condition that the reaction of interest is peripheral, like the radiative captures involving p, d, t, ^{3}He and α-particles in the stellar environment. The method will be presented, marking the key points of the theoretical framework and the advantages of its usage. An experimental overview of the method will be given, using the ongoing data analysis of the ^{26}Mg(d,p)^{27}Mg reaction, that is interesting due to its mirror reaction, ^{26}Si(p,γ)^{27}P. The latter is considered to be important as a constraint to the production of ^{26}Al and ^{26m}Al, that is among the most debated elements produced by novae and x-ray bursts[3,4]. Galactic ^{26}Al can be produced through the ^{24}Mg(p,γ)^{25}Al(β^+)^{25}Mg(p,γ)^{26}Al reaction chain, complicated by the presence of the well-known short-lived isomer ($T_{1/2}$ = 6.34s) mentioned above. This route can be bypassed by the ^{25}Al(p,γ)^{26}Si(p,γ)^{27}P. In high-temperature novae ($T_9 \approx 0.4$) ground and isomeric states are supposed to be in thermal equilibrium[5], and the latter can be produced by ^{26}Si(β^+)^{26m}Al. The depletion of ^{26}Si via the (p,γ) reaction can be important to better understand the ratio of abundances between the ground and the isomeric state[6]. Some other remarkable results obtained using ANC will also be presented[7,8,9].

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Nuclear astrophysics studies at NIPNE

L Trache[1]

[1] *IFIN - HH, Bucuresti, Romania*

I will present results of doing nuclear astrophysics research at the National Institute for Physics and Nuclear Engineering, Bucharest-Magurele in the last 2-3 years. Own Nuclear Astrophysics Group (NAG) is focused on the basic types of experiments:

- Direct measurements at low and very low energies with ion or alpha beams from the local 3 MV tandetron accelerator. We concentrate on activation measurements. The use of the ultra-low background laboratory in a salt mine at Slanic-Prahova, about 120 km away and of a beta-gamma coincidence unit at home is providing competitive sensitivity.
- Indirect measurements done with beams at international facilities with radioactive beams: TAMU and RIBF RIKEN.

With help from colleagues, I will present some theory advances, too.

Role of Clustering in Nuclear Astrophysics

Neven Soić[1]

[1] *Rudjer Bošković Institute, Zagreb Croatia*

Nuclear structure and reaction dynamics are strongly linked: reacton cross section reflects the structure of colliding nuclei while appropriate selection of colliding nuclei and their relative energy can magnify the specific structural property of nuclei involved in the reaction. The effects of nuclear structure on reaction dynamics are especially pronounced at low relative energies between interacting nuclei, what is a standard condition for the nuclear reactions in astrophysical environments. In this condition, relative energy between colliding nuclei can be such that composite nuclear systems possess resonant states of adequate properties to stongly enhance the reaction cross section. Another possibility is that specific transfer channel of one or more nucleons is enhanced by structure of colliding nuclei. Clustering, appearance of two- or three-center structures [1], is particularly pronounced in light nuclei and it has important consequences on dynamics of reactions between the light nuclei. The basic building unit of the cluster structures in light nuclei is the ^{4}He nucleus - α-particle, the most stable and one of most tightly bound light nuclei. In the same time, the ^{4}He is the second most abundant nucleus in the Universe (approximately 23 %, protons approximately 71 %) and for this reason the reactions with the α-particles are of crucial importance for production of energy and nucleosynthesis in the stars. Thereto, main source of energy in all astrophysical sites are reactions between light nuclei, with many of them determined by the cluster structure of reacting nuclei.

In this lecture some key examples of the astrophysically relevant nuclear reactions governed by cluster structure of reactiong nuclei will be presented. The first of them is the three α-particles fusion into ^{12}C via the Hoyle state [2], the pathway over the A = 5 and 8 gaps which makes possible production of heavier nuclei. Reactions of the α-particles with carbon and oxygen isotopes relevant for the nucleosynthesis in massive stars will be also briefly presented.

In heavier nuclei, clustering based on heavier building blocks than α-particle may appear and the most known example is the ^{12}C + ^{12}C clustering in ^{24}Mg. While there are many evidences of this clustering at high excitations, its existence in Gamow window for the carbon - carbon fusion is still hot research topic. The recent study [3] has provided the first evidence for resonance in the Gamow window which enhance the rate of this process. The number of other studies is underway using different approaches to measure extremely low reaction rate of this process, from direct measurements at low energy to various indirect techniques aiming to identify and characterize resonances in the Gamow window.

Finally, brief overview of some experimental techniques to study clustering effects in reactions relevant for nuclear astrophysics will be presented.

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Dispersion (asymptotic) theory of charged-particle transfer reactions and nuclear astrophysics

R. Yarmukhamedov[1] and K. I. Tursunmakhatov[2]

[1] *Institute of Nuclear Physics, Tashkent100214, Uzbekistan*
[2] *Physical and Mathematical Department of Gulistan State University, 20100 Gulistan, Uzbekistan*

In the present work, a new asymptotic theory is proposed for the peripheral sub- and above-barrier transfer $A(x,y)B$ reaction in the framework of a three-body (A, a and y) model, where $x = y + a$, $B = A + a$ and a is a transferred particle. The asymptotic theory is based on the idea of the fact that, firstly, a peripheral reaction is governed by the nearest to the physical region (-1$\leq \cos\theta \leq 1$) singularity (ξ) of the reaction amplitude located at the point $\cos\theta = \xi$ (θ is the scattering angle in the c.m.s.). Secondly, the dominant role played by the nearest singularity is the result of the surface nature of this reaction. In this case, the dominant contribution to the peripheral reaction comes from the surface and outer regions of nuclei corresponding to $R \geq R_{\rm ch}$, where R and $R_{\rm ch}$ are the relative distance between the center of mass of the colliding nuclei and the channel radius, respectively. These regions for the reaction amplitude, decomposed in the partial waves (l_i), correspond to the low partial waves with $l_i < k_i R_{\rm ch}$ (l_i= 0,1,2, and k_i is a wave number of the colliding nuclei) for sub-barrier energies ($k_i = \sqrt{2\mu_{Ax}E_i}/\hbar \to 0$, $E_i \to 0$ and μ_{Ax} is the reduced mass of the colliding nuclei) and to the peripheral partial waves with $l_i \geq k_i R_{\rm ch}$ >>1 for the above-barrier energies ($\sim$10 -15 MeV per nucleon).

In the proposed asymptotic theory, the main advantage of the dispersion method and the distorted wave Born approximation (DWBA) are combined. At this, the allowance of the contribution of the three-body (A, y and a) Coulomb dynamics of the transfer mechanism to the peripheral partial amplitudes with $l_i \geq k_i R_{\rm ch}$, which is determined by the nearest singularity of the reaction amplitude, is done in a correct manner.

The explicit form of the differential cross section (DSC) for the reaction under consideration is derived. The DCS is expressed directly in terms of the product of the squared asymptotic normalization coefficients (ANCs) for $y + a \to x$ and $A + a \to B$.

The results of the analysis of the experimental DCSs both of the sub-barrier ^{19}F(p, α)^{16}O reaction at different projectile energies and of the above-barrier ^{16}O(^{3}He, d)^{17}F, ^{9}Be(^{10}B, ^{9}Be)^{10}B(g.s.) and ^{11}B(^{12}C, ^{11}B)^{12}B(g.s.) reactions are presented.

As a result, the values of the squared ANCs for $^{16}{\rm O} + t \to {}^{17}$F(g.s.), $^{16}{\rm O} + t \to {}^{17}$F(0.495 MeV), $^9{\rm Be} + p \to {}^{10}$B(g.s.) and $^{11}{\rm B} + p \to {}^{12}$C(g.s.) are found. They are equal to 583.3±46.1, 1.35±0.14, 6216±632, 4.35±0.19 and 311.6±13.3 fm^{-1}, respectively. The ANC values obtained for $^9{\rm Be} + p \to {}^{10}$B(g.s.), $^{11}{\rm B} + p \to {}^{12}$C(g.s.) and $^{16}{\rm O} + t \to {}^{17}$F are also used for the estimation of direct astrophysical S factors corresponding to the nuclear-astrophysical ^{9}Be(p, γ)^{10}B(g.s.), ^{11}B(p, γ)^{12}C(g.s.) and ^{16}O(p, γ)^{17}F reactions at E= 0 and 25 keV. The obtained results are compared with those from other authors.

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Silicon Carbide detectors: a concrete perspective for nuclear Astrophysics activities

S Tudisco[1]

[1] *Laboratori Nazionali del Sud, INFN, Catania, Italy*

Silicon Carbide represent the new challenge in the detectors technology. Silicon Carbide (SiC) is a wide indirect band gap semiconductor. Due to its composition SiC it is the only stable compound in the binary phase diagram of the two groups IV elements, silicon and carbon. Of all the wide band gap semiconductors, silicon carbide is presently the most intensively studied one and the one with the highest potential to reach market maturity in a wide field of device applications, such as high-temperature electronics, biomedical sensors, UV photosensors, particle and X-ray detectors. SiC is seriously considered as a valid alternative to silicon for the production of radiation hard devices, since it gives the opportunity to couple the excellent properties of silicon detectors (efficiency, linearity, resolution) with a much larger radiation hardness, thermal stability and insensitivity to visible light. For the nuclear and particles community is very important to have devices able to operate at high fluences (up to 1014 cm-2) and at high rate, in order to measure cross sections of very rare phenomena.

Advanced diagnostics for experiments of laser-matter interaction of astrophysical interest

F Consoli[1], P.L. Andreoli[1], A. Bonasera[2,3], M. Cipriani[1], G. Cristofari[1], R. De Angelis[4], G. Di Giorgio[1], D. Giulietti[4], M. Salvadori[1,5,6]

[1] *ENEA, Fusion and Nuclear Safety Department, C.R. Frascati, Frascati, Italy*
[2] *Texas A&M University, Cyclotron Institute, College Station, Texas, USA*
[3] *INFN, Laboratori Nazionali del Sud, Catania, Italy*
[4] *Physics Department of the University and INFN, Pisa, Italy*
[5] *University of Rome "La Sapienza", Rome, Italy*
[6] *INRS-EMT, Varennes, Québec, Canada*

In the last twenty years a remarkable research activity has regarded the study of astrophysical processes by means of laboratory experiments of high-energy and high-power laser interaction with matter. A few examples are the determination of nuclear fusion cross-sections at low energies in laser-plasmas [1], the formation and morphology of protostellar plasma jets [2], and the acceleration process of energetic electrons by astrophysical shocks [3]. These experimental studies require advanced diagnostics for the plasma and the full spectrum of particle and electromagnetic radiation generated by the intense interactions, and for their evolution over time. This presentation will supply a general overview of the diagnostic instruments commonly used in the main laser facilities, and will give details for those more specifically developed and optimized for experiments of astrophysical interest [1-6].

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The PANDORA project: an experimental setup for measuring in-plasma β-decays of astrophysical interest

D Mascali[1]

[1] *Laboratori Nazionali del Sud, INFN, Catania, Italt*

Experiments performed on Storage Rings have shown that lifetimes of beta-radionuclides can change dramatically as a function of the ionization state. PANDORA (Plasmas for Astrophysics, Nuclear Decay Observation and Radiation for Archaeometry) aims at measuring, for the first time, nuclear β-decay rates in stellar-like conditions, especially for radionuclides involved in nuclear-astrophysics processes (BBN, s-processing, CosmoChronometers, Early Solar System formation). Compact magnetic plasma traps, where plasmas reach density ne∼1011-1014 cm^{-3}, and temperature Te∼0.1-30 keV, are suitable for such studies. The decay rates can be measured as a function of the charge state distribution of the in-plasma ions. The collaboration is now designing the plasma trap able to reach the needed plasma densities, temperatures and charge states distributions. A first list of radioisotopes, including tens of physics cases of potential interest is now available. Possible physics cases include, among the others, 204Tl, 63Ni, 60Co, 171Tm, 147Pm, 85Kr 176Lu and the pairs 187Re-187Os and 87Sr-87Rb, which play a crucial role as cosmo-clock. Physics cases are now under evaluation in terms of lifetime measurements feasibility in a plasma trap.