The 9th European Summer School on Experimental Nuclear Astrophysics

September 17-24, 2017
Santa Tecla, Sicily, Italy

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

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Lecturers

9^{th} *European Summer School on Experimental Nuclear Astrophysics*
17-24 September 2017, Santa Tecla, Italy

An Introduction to (Experimental) Nuclear Astrophysics

M. Aliotta[1]

[1] *University of Edinburgh*

Of all the chemical elements that make up the visible universe, only hydrogen, helium, and traces of others were produced during the first few minutes after the Big Bang. The creation of all other elements from carbon to uranium is the result of a complex pattern of nuclear reactions that take place in many and different astrophysical sites, from quiescent stars like our Sun to fierce explosions like novae and supernovae. Understanding these nuclear processes and how they govern the birth, life and death of stars is at the heart of Nuclear Astrophysics, a truly interdisciplinary field that requires inputs from astronomy, cosmology, nuclear-, particle-, and atomic physics. Incredible progress has been achieved over the last 60 years, since the seminal paper by Burbidge et al. in 1957, which marks the beginning of Nuclear Astrophysics. Yet, many open questions remain and provide fertile grounds for further explorations.

In these lectures, I will present an overview of the main advances and breakthroughs of recent years and discuss some of the key challenges that lay ahead for nuclear astrophysics experiments.

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r-process observations

W. Aoki[1]

[1] *National Astronomical Observatory of Japan*

The r-process nucleosynthesis in the Universe is constrained by observations of chemical abundances of old stars that should record the products of the r-process events in the early Universe. I will provide a brief overview of the observational technique to determine chemical abundances of stars, including the reliability and problems of the measurements. Targets of observations are stars in different populations of the Milky Way Galaxy and surrounding dwarf galaxies, providing different kind of constraints on the understanding of the r-process. Recent progress in observational studies to identify the r-process sites will be reviewed.

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Indirect methods for nuclear astrophysics

C. Bertulani[1]

[1] *Texas A&M University-Commerce*

I will discuss recent developments in indirect methods used in nuclear astrophysics to determine the capture cross sections and subsequent rates of various stellar burning processes, when it is difficult to perform the corresponding direct measurements. I will present the basic concepts of Asymptotic Normalization Coefficients, the Trojan Horse Method, the Coulomb Dissociation Method, (d,p), and charge-exchange reactions.

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Recent experiments at LUNA: a detailed study and its astrophysical impact

A. Best[1,2]

[1] *Universitá "Federico II" Napoli*
[2] *INFN - Sez. Napoli*

Direct measurements of cross sections for nuclear astrophysics strive to provide data directly inside the relevant energy regions of the various burning processes, thus avoiding having to rely on extrapolations or indirect methods and their associated uncertainties. The LUNA facility at the Gran Sasso National Laboratory has for over 20 years specialised on measuring very low energy cross sections. The detection of the low event rates (sometimes below a few reactions per day) is possible by exploiting the strong background reduction provided by the rock overburden of the underground location. Together with a short introduction on the experimental backgrounds we want to give an insight into the daily life at LUNA. For that, we showcase the recently completed measurement campaign of the reaction $^{18}O(p,\gamma)^{19}F$. This reaction was measured on the solid target beamline, using a high-efficiency 4π BGO and a high-resolution HPGe detector in order to extract the low energy total cross section and (using the HPGe) information on higher energy resonant branchings and the individual direct capture reaction components.

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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.*

The plasma astrophysical S-factor for the ^{3}He(d;p)^{4}He 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 ^{3}He atoms. The experiments were performed at the Petawatt laser facility, University of Texas, Austin-USA. Different proportions of D_2 and ^{3}He or CD_4 and ^{3}He 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 ^{3}He(d;p)^{4}He reaction was measured in order to extract the astrophysical S-factor at low energies. Recent results obtained at the ABC-laser facility, ENEA-Frascati, Italy on the p+^{11}B,^{6}Li+^{6}Li and d+^{6}Li systems will be discussed. Using the SGII laser facility in Shanghai (8 laser beams, ps to ns time duration up to 16KJ energy) we discuss preliminary results on highly compressed and hot CD_2 targets and explore the possibility of measuring reaction rates in such conditions.

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[5] Progr.Theor.Phys. Supplement No. 154, 2004, 261;
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The LUNA experiment: past and future

C. Broggini[1]

[1] *INFN - Sez. Padova*

LUNA started measuring the cross section of a few key reactions of astrophysical interest 25 years ago under Gran Sasso. During the lecture I will first discuss the main advantages of a deep underground location. Then, I will describe the contributions provided by LUNA to the solution of the solar neutrino problem. Finally, the future of LUNA with the new 3.5 MV accelerator will be outlined.

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Statistical Methods for Thermonuclear Reaction Rates and Nucleosynthesis Simulation

A. Coc[1]

[1] *Centre de Sciences Nucléaires et de Sciences de la Matière (CSNSM), CNRS/IN2P3, Université Paris Sud 11, UMR 8609, Bâtiment 104, 91405 Orsay Campus (France)*

Rigorous statistical methods for estimating thermonuclear reaction rates and nucleosynthesis are becoming increasingly established in nuclear astrophysics. The main challenge being faced is that experimental reaction rates are highly complex quantities derived from a multitude of diffferent measured nuclear parameters (e.g., astrophysical S-factors, resonance energies and strengths, particle and gamma-ray partial widths). We discuss the application of the Monte Carlo method to reaction rates dominated by many resonances and methods to treat rates associated with non-resonant reactions. We address three distinct, but related, questions. First, given a set of measured nuclear parameters, how can one best estimate the resulting thermonuclear reaction rates and associated uncertainties? Second, given a set of appropriate reaction rates, how can one best estimate the abundances from nucleosynthesis (i.e., reaction network) calculations? Third, beyond standard sensitivity studies, when a single reaction rate is changed at a time, can sensitivity studies based on correlations between Monte Carlo sampled rates and abundances identify new important reactions to be investigated further.

Reaction studies with magnetic separators

M. Couder[1]

[1] *University of Notre Dame*

Recoil separators are used in nuclear astrophysics for two reasons: (i) to allow a certain category of studies with radioactive beam and (ii) to reduce background and target complications when high intensity stable beams are used. In this talk examples of successful recoil separators and associated experiments will be used to describe the critical characteristics required to permit meaningful measurements. New separators will be discussed as well.

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s-process in stellar sites

S. Cristallo[1,2]

[1] *INAF, OA Teramo*
[2] *INFN - Sez. Perugia*

The s-process plays a major role in the nucleosynthesis history of the Universe, being responsible for the production of half the elements heavier than iron. I will describe the stellar sites where the s-process is at work, with particular emphasis on Asymptotic Giant Branch Stars. Moreover, I will highlight the nuclear aspects of this nucleosynthetic process, showing the importance of neutron production and neutron capture reaction rates.

Resonant Elastic Scattering Measurements

F. de Oliveira[1]

[1] *GANIL*

In nuclear astrophysics, we are often interested by radiative capture reactions, e.g. X(p,γ)Y, cross sections measured at low energy. At the same energy, the cross section for the elastic scattering reaction X(p,p)X is usually large ($>$ 100 barn/sr). It follows that the excitation function of this reaction can be measured rapidly. Even with radioactive beams, it is also possible to measure the excitation function relatively easily in inverse kinematics using a thick target. Analysis of the elastic scattering excitation function, and calculations of the reaction, show that the cross section is dominated by Rutherford elastic scattering at very low energy, and generally, it also shows peaks and interferences patterns corresponding to the presence of resonances in the compound nucleus (Y=X+p). Resonant states properties can extracted from this excitation function. The properties of the resonances, i.e. resonance energy, partial and total widths, and spin, can be extracted from the analysis of the shape of the peaks using the R-Matrix formalism.

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Heavy Elements Nucleosynthesis

Mounib F. El Eid

[1] *American University of Beirut, Deparment of physics*

This lecture deals with the important subject of the nucleosynthesis of heavy elements in the Galaxy. After an overview of several observational features, the physical processes responsible mainly for the formation of heavy elements will be described and linked to possible stellar sites and to galactic chemical evolution. In particular, we focus on the neutron-capture processes, namely the s-process (slow neutron capture) and the r-process (rapid neutron capture) and discuss some problems in connection with their sites and their outcome. The lecture has the aim to give a brief overview about the exciting subject of the heavy element nucleosynthesis in the Galaxy, emphasizing its importance to trace the galactic chemical evolution and illustrating the challenge of this subject.

Low-energy direct measurements: difficulties and perspectives

Zs. Fülöp[1]

[1] *Institute for Nuclear Research (MTA Atomki), Debrecen, Hungary*

Technical requirements of low energy direct measurements for nuclear astrophysics will be presented using the example of experiments relevant to p-process nucleosynthesis [1]. In addition to reaction rate determination experiments, the importance of elastic scattering studies in the relevant mass and energy range will be discussed [2]. The extension of activation technique with X-ray detection will be presented as a tool to increase the sensitivity of activation experiments [3].

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[2] P. Mohr et al., Atomic Data and Nuclear Data Tables 99 (2013) 651

[3] Gy. Gyrky et al., Eur. Phys. J. A in preparation

Neutron Induced Reactions at BBN Energies

M. Gai[1]

[1] *LNS at Avery Point, University of Connecticut, Groton, CT 06340, USA*

The Soreq Applied Research Facility (SARAF) [1], at the Soreq Nuclear Center in Israel when operating (in phase I) with the Liquid Lithium Target (LiLiT) [2-4] produce some of the most intense epi-thermal neutron beams available today (5 1010 $n/cm^2/sec$). The so produced neutron energy distributions resemble a quasi Maxwellian distribution with energies (35 - 100 keV) [5-6] that perfectly match the conditions during Big Bang Nucle- osynthesis. Accurate measurement of the baryon density by WMAP renders Big Bang Nucleosynthesis (BBN) a parameter free theory with only inputs from measurements of the relevant (12 canonical) nuclear reactions [7]. BBN predicts with high accuracy the measured abundance of deuterium, helion and helium relative to hydrogen, but it over-predicts the abundance of ^{7}Li relative to hydrogen by a factor of approximately three and more than three sigma difference from the observed value; hence the Primoridal ^{7}Li Problem [8]. We will discuss a world wide attempt to measure the interaction of neutrons with ^{7}Be [9-11] with an emphasize on the SARAF measure- ment [12], the only measurement in the BBN window (50 keV), in order to measure the rate of destruction of ^{7}Be by neutrons. We examin the last possible venue for solving the Primordial ^{7}Li Problem and our results reveal the lack of standard nuclear physics solution to the Primordial ^{7}Li Problem.

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[3] M. Paul, A. Arenshtam, S. Halfon, D. Kijel, M. Tessler, L. Weissman, D. Berkovits, Y. Eisen, I. Eliyahu, M. Friedman, G. Feinberg, A. Kreisel, I. Mardor, G. Shimel, A. Shor, I. Silverman, J. Radioanal. Nucl. Chem. 305, 783 (2014).
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[6] M. Tessler et al., Phys. Lett. B751, 418 (2015).
[7] M. S. Smith, L. H. Kawano, and R. A. Malaney, Astrophys. J. Suppl. 85, 219 (1993).
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[9] Dorothea Schumann, Massimo Barbagallo, Thierry Stora, Ulli Koester and Moshe Gai, Nuclear Physics News, 26:4, 20 (2016).
[10] Massimo Barbagallo et al., and the n TOF collaboration, Phys. Rev. Lett. 117, 125701 (2016).
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Trojan Horse Method experiments with radioactive ion beams

M. Gulino[1,2], S. Cherubini[1,3], G. G. Rapisarda[1,3], S. Kubono[4], L. Lamia[3], M. La Cognata[1],R.G. Pizzone[1] H. Yamaguchi[5], S. Hayakawa[5], Y. Wakabayashi[5], N. Iwasa[6], S. Kato[7], T. Komatsubara[8], T. Teranishi[9], A. Coc[10], N. De Séréville[10], F. Hammache[10], G. Kiss[12], S. Bishop[3,13], D. N. Binh[5,14]C. Spitaleri[1,3]

[1] *INFN-LNS, Catania, Italy*
[2] *Università di Enna Kore, Enna, Italy*
[3] *Dipartimento di Fisica e Astronomia, Università di Catania, Catania, Italy*
[4] *RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
[5] *CNS, University of Tokyo, Wako Branch, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
[6] *Department of Physics, Tohoku University, 6-6 Aoba, Sendai, Miyagi 980-8578, Japan*
[7] *Department of Physics, Yamagata University, Yamagata 990-8560, Japan*
[8] *Institute of Physics, University of Tsukuba, Tennodai 1-1-1, Tsukuba, Ibaraki 305-8577, Japan*
[9] *Department of Physics, Kyushu University, Fukuoka 812-8581, Japan*
[8] *Rare Isotope Science Project, IBS, Yuseong-daero, Yuseong-gu, Daejeon 305-811, Korea*
[9] *Department of Physics, Kyushu University, Fukuoka, Japan*
[10] *Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, IN2P3, F-91405 Orsay, France*
[11] *Institut de Physique Nucléaire, IN2P3, F-91405 Orsay, France*
[12] *Institute for Nuclear Research (MTA-ATOMKI), Debrecen, Hungary*
[13] *TUM, Garching, Germany*
[14] *30 MeV Cyclotron Center, Tran Hung Dao Hospital, Hoan Kiem District, Hanoi, Vietnam*

The Trojan Horse Method (THM) has been recently extended to reactions induced by radioactive ion beams (RIB) [1,2]. To this aim, an improvement ofthe typical experimental set-up was mandatory. Indeed, necessary condition for the applicability of the method is the selection of the events that proceed via quasi-free processes in a three body reaction $A + a \rightarrow b + c + s$, where the nucleus a, called Trojan Horse nucleus, has a strong cluster structure x-s [3,4]. For the identification of the quasi-free events, as only 2 of the 3 outgoing particles are detected in the experiment, it is necessary to reconstruct the kinematic of the reaction, making an hypothesis on the nature of the undetected nucleus. The kinematical variables are very sensitive to the angles of the tracks of the outgoing products. For this reason, in the usual THM experiments, the beam spot is reduced to 1 or 2 mm and position sensitive detectors having a resolution of a millimeter are used in the experimental set-up. Moreover, as the quasi-free events are a small fraction of the whole statistics (generally of the order of 10%, depending strongly on the reaction), it is mandatory to collect enough events to obtain reasonable statistical errors.
All these requirements hardly match with the typical low intensity and large divergence of RIBs. To overcome these difficulties, more efficient experimental set-up have been developed. The study of the $^{18}F(p, \alpha)^{15}O$ reaction will be discussed and some results will be presented.
A very interesting application of the THM to RIB induced reactions is the study of neutron induced reactions on radioactive isotopes, even if they have a short lifetime [5,6]. Preliminary results on this topic will be presented.

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[2] R.G. Pizzone et al., EPJA, 52 24 (2016)
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Transfer reactions for Nuclear Astrophysics

F. Hammache [1]

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

Direct measurements at stellar energies are very challenging - if at all possible. This is essentially due to the very low cross-sections of the reactions of interest (especially when it involves charged particles), and/or to the radioactive nature of many key nuclei. Direct measurements with charged particles are often performed at higher energies and then extrapolated down to stellar energies using R-matrix calculations. However, these extrapolations are delicate because of the possible existence of unobserved low-energy or sub- threshold resonances. In order to bypass the difficulties related to direct measurements, indirect methods such as transfer reactions are used. These experiments are usually performed at higher energies and their conditions are relatively less stringent than in direct measurements. However, these methods rely on theoretical models for which the input parameters may be an important source of systematic uncertainties and thus need to be determined carefully.
In this lecture, I will first give a short overview on the difficulties related to direct measurements, then I will describe the transfer reaction method and the theoretical concept behind and finally illustrate the method with recent performed studies.

Nuclear-data input to the r-process: the case of β-decay properties

K.L. Kratz[1], O. Hallmann[1] and K. Farouqi[1]

[1] *Fachbereich Chemie, Pharmazie & Geowissenschaften, Universität Mainz, D-55128, Mainz, Germany*

Attempts to explain the origin of the r-process elements in our Solar-System still face the entwined uncertainties stemming from the extrapolation of nuclear structure from the line of β-stability to the neutron drip line, the use of inconsistent sources of different properties (e.g. nuclear masses, β-decay properties and reaction rates), and the insufficient understanding of the astrophysical conditions of the different r-process "varaints", which are often difficult to disentangle. In this lecture, we will focus on the two "integral" β- decay quantities, i.e. the half-life $T_{1/2}$ and the delayed- neutron emission probability P_n, which are among the easiest measurable properties for extremely neutron-rich isotopes. Theoretically, both quantities are interrelated via their usual definition in terms of the β-strength function $S\beta(E)$. As we have already demonstrated in the past, taken together these two quantities ca indicate some primary nuclear structure at different energy regions of the $S\beta(E)$. Starting with some historical examples about their influence on the r-process matter flow and the respective abundance distributions, we will then discuss comparisons of our nuclear and astrophysics model predictions with the recent $T_{1/2}$ data from RIKEN in the REE region.

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Experimental Challenge to High-Temperature Hydrogen Burning

S. Kubono[1,2]

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

Hydrogen burning at extremely high temperatures is of great interest in nuclear astrophysics. They may occur in the rp-process in type Ia X-ray bursts on the surface of neutron stars, and the νp-process in type II supernovae. Both nucleosynthesis run through far from the line of stability of the neutron- deficient nuclear region under extremely high-temperature and high-density conditions. This burning is, thus, considered to be one of the production mechanisms of the p-nuclei up to around mass 100. Especially, the production of the anomalously abundant p-nuclei at A = 80-100 is of great interest.

In order to clarify such nucleosynthetic scenarios, nuclear physics information of these nuclei are definitely needed, but very few are known yet. The hydrogen burning at extremely high-temperature, around a few Giga Kelvin starts from the pp-chain region, and possibly runs up to somewhere around a mass 100 region. Thus, the first problem is to know the breakout process from the pp-chain region, which even affects to the yields of heavy elements. Along the pathway, there are several possible waiting points and bottle necks on the rp-process. This should be the second problem of the study. The explosive burning might stall for some time there, resulting in possibly a different X-ray light curve, or a double peak observation and less production of heavier elements beyond. In the νp-process, these waiting points might be discarded by the neutron induced reactions such as (n,p) and (n,γ) reactions on the waiting point nuclei. The third problem is the production of p-nuclei mentioned above by the burning. And, the fourth problem is the termination process, which is also an important and interesting question. Especially, this problem might be relevant to possible heavy element observation in X-ray bursts.

I will discuss recent experimental efforts to clarify these problems, especially the breakout process from the pp-chain region, to which a detailed nuclear reaction studies are going on. As for the waiting point, I will discuss a study for the possible ^{72}Kr waiting point. I also touch on a recent precision mass measurement that will define the contribution of p-nucleus, ^{84}Sr production, and the termination of the burning.

Nuclear Astrophysics with Gamma Beams at ELI-NP

C. Matei[1]

[1] *ELI-NP*

The Extreme Light Infrastructure Nuclear Physics facility (ELI-NP), under construction in Bucharest-Magurele, Romania, will deliver very intense brilliant beams. Several very important nuclear reactions related to Big Bang Nucleosynthesis and other stages of stellar burning have been selected for the first measurement campaigns.
The ^{7}Li(γ,^{3}H)^{4}He reaction is of interest for the longstanding Cosmological Li problem and for verifying several recent theoretical predictions. Although most measurements over the last 30 years have concentrated in an energy range below 1.5 MeV, measurements at higher energies could restrict the extrapolation to astrophysically important energies. A step-by-step exercise will be proposed to the audience to help prepare the proposed experiment using ELISSA, the new silicon-strip detector array at ELI-NP.
The ^{12}C$(\alpha,\gamma)^{16}$O radiative capture reaction is one of the most important reactions in nuclear astrophysics as its reaction rate strongly influences the present C/O ratio in the Universe. We propose to measure the total cross section and angular distributions in the ^{16}O$(\gamma,\alpha)^{12}$C reaction using a Time Projection Chamber detector with electronic readout. A review of a very contested experiment will help the audience understand the concept of precision in nuclear astrophysics.

Primordial Nucleosynthesis

Grant J Mathews[1]

[1] *University of Notre Dame, Center for Astrophysics, Department of Physics, Notre Dame, IN 46556 USA*

Primordial nucleosynthesis remains as one of the pillars of modern cosmology [1]. It is the testing ground upon which many cosmological models must ultimately rest. It is our only probe of the universe during the important radiation-dominated epoch in the first few minutes of cosmic expansion.

The first lecture in this series will review sthe basic equations of space-time, cosmology, and big bang nucleosynthesis [1]. We will summarize the current state of observational constraints on primordial abundances along with the key nuclear reactions and their uncertainties. In particular, we summarize which nuclear measurements are most crucial during the big bang [2].

The second lecture in this series will summarize the key issues in big bang cosmology [1] and how it is that big bang nucleosynthesis can help to answer these questions. We will review various cosmological models and their constraints. In particular, we analyze the constraints that big bang nucleosynthesis places upon the possible time variation of fundamental constants, along with constraints on the nature and origin of dark matter and dark energy [1], long-lived supersymmetric particles [3], cosmic phase transitions [1], extra dimensions and or new relativistic particles [4] gravity waves, and the primordial magnetic field [5].

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RIB production and related experiments at EXOTIC

M. Mazzocco[1,2]

[1] *Dipartimento di Fisica e Astronomia, Università di Padova, Padova, Italy*
[2] *INFN - Sezione di Padova, Padova, Italy*

Radioactive nuclei have a very deep relevant in many different scenarios of astrophysical interest, from the Big Bang nucleo-synthesis to supernova explosions. Several Nuclear Physics laboratories around the world have been presently constructing new facilities dedicated to the delivery of Radioactive Ion Beams (RIBs). There exist two main production techniques, In-Flight and ISOL, which will be reviewed in this contribution. In particular, we will concentrate on the production of light weakly-bound RIBs at the facility EXOTIC [1,2], located at INFN-LNL (Italy). We will describe two recent experiments aimed at studying the key-reaction the Big-Bang Nucleo-synthesis network ^{7}Be(n,^{4}He)^{4}He [3] and the reaction dynamics induced by the ^{7}Be RIB on a ^{208}Pb target at Coulomb barrier energies [4].

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[3] L. Lamia et al., LNL-Proposal 15.13 (2015).
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Neutron induced reaction cross section measurements for nuclear astrophysics at CERN n_TOF

A. Mengoni[1]
on behalf of the n_TOF Collaboration

[1] *ENEA and INFN, 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,α) and (n,p) on ^{7}Be), reactions and nuclear spectroscopy for the s-process neutron sources.

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Essentials of the macroscopic-microscopic folded-Yukawa approach and examples of its record in providing data for r-process and neutron-star crust studies

P. Möller

P. Moller Scientific Computing and Graphics, Inc., P. O. Box 1440, Los Alamos, NM 87544, USA

The macroscopic-microscopic model based on the folded-Yukawa single-particle potential and a "finite-range" macroscopic model is probably the approach that has provided the most reliable predictions of a *large* number of nuclear-structure properties for *all* nuclei between the proton and neutron drip lines. I will describe some basic features of the model and the development philosophy that may be the reason for its success. Examples of quantities modeled within the same model framework are, nuclear masses, ground-state level structure, including spins, ground-state shapes, fission barriers, heavy-ion fusion barriers, sub-barrier fusion cross sections, β-decay half-lives and delayed neutron emission probabilities, shape coexistence, and α-decay Q_α energies to name a few. I will show how well it predicted various properties measured *after* published results. Finally I will show some applications by "our collaboration" to r-process studies and neutron-star weak-interaction networks. Rather than giving references here to this work I refer to our web site which has many pedagogical papers as well as detailed, complete model specifications and astrophysical applications (note the "interactive" link)

http://t2.lanl.gov/nis/molleretal/

ANC experiments

J. Mrazek [1]

[1] *NPI CAS*

Astrophysical reactions proceed typically at low energies, where the direct measurements are either difficult or even not possible. Therefore several indirect methods were developed. The ANC method - method of Asymptotic Normalization Coefficients - exploits binary nuclear reactions at medium energies (typically 10 MeV/A) to reveal a direct part of radiative capture reactions (e.g. (p,γ)). This method was developed by Akram Mukhamedzhanov during his stay in NPI CAS in 90ties and number of experiments were performed in NPI U120M cyclotron in collaboration with INFN-LNS, TAMU, ATOMKI.

RIB and explosive nucleosynthesis

S. Nishimura[1] for the RIBF Decay Collaborations

[1] *RIKEN Nishina Center, Wako, Saitama 351-0198, Japan*

A rapid-neutron capture process (r process), sequence of neutron-capture and -decay pro- cesses, is believed to be responsible for the synthesis of approximately half of nuclides heavier than iron. Although the condition of astrophysical r-process site is expected to be extremely high-density neutron environment, its sites is not identified as still a long-standing puzzle.

The abundance pattern of the r-process elements is expected to be sensitive to the r-process conditions and nuclear properties. Recently, sensitivity study of nuclear properties in r-process has been tested in various conditions such as low-entropy hot wind, high entropy hot wind, cold wind, and neutron star merger [1]. The results suggest critical roles of nuclear properties of very neutron-rich nuclei (mass, β-decay rates, β-delayed neutron emission probabilities, neutron-capture rates). In the last decades, production of r-process elements has been simulated using various theoretical models, where significant improvement in its uncertainties is expected from the experimental feedback.

High intensity radioactive isotope beam facility (RIBF) start producing exotic nuclei at RIKEN using in-flight fission of ^{238}U-beam as well as fragmentations of ^{48}Ca, ^{78}Kr, and ^{124}Xe beams at RIKEN. About 440 exotic nuclei were transported to our decay spectrometer (EURICA), consisting of 12 EUROBALL Germanium Cluster detectors and β-ray detectors (WAS3ABi) [2]. The impacts of 144 β-decay half-lives of neutron-rich nuclei were investigated in the condition of high entropy hot wind conditions [3,4]. In this talk, latest results and future perspectives relevant to explosive nucleosynthesis will be presented.

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Gas detectors for nuclear physics experiments

Dimitra Pierroutsakou[1]

[1] *INFN - Sezione di Napoli, Via Cintia, I-80126 Napoli, Italy*

Gas detectors are planned or being constructed at every nuclear physics facility. In this lecture I will present the operation principle and the different kinds of gas detecting systems operating in high-energy and low-energy physics environments, with particular focus on the requirements of nuclear physics experiments employing low-energy Radioactive Ion Beams (RIBs). I will show examples of gas detectors [1] used at the RIB in-flight facility EXOTIC (INFN-LNL, Italy) [2-6] dedicated to the ion-beam tracking, to energy measurements and particle identification of the reaction charged particles. Finally, the technique of using an active target in inverse kinematics nuclear physics experiments with RIBs, will be discussed together with some key improvements that would extend applicability and improve functionality, also in view of the more intense RIBs of future facilities (SPES, SPIRAL2, ISOLDE, ...).

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Explosive nucleosynthesis: from the stars to the labs

H. Schatz[1]

[1] *NSCL, Department of Physics and Astronomy, JINA-CEE, Michigan State University*

I will discuss the nuclear processes in transiently accreting X-ray binaries, their link to open questions and observational puzzles, the ways we can identify critical nuclear physics, and various experimental approaches used to address these. The nuclear processes of interests are the rapid proton capture process, explosive carbon burning, electron capture, Urca processes, and high density fusion reactions.

Stellar structure and evolution

O. Straniero[1]

[1] *INAF-Osservatorio Astronomico di Teramo*

Understanding the final destiny of stars with different initial mass is the ultimate goal of stellar evolution. In this context, the Chandrasekhar limit for the mass of stable degenerate cores plays a fundamental role. As a star evolves its core mass increases. This process continues until the energy sources (as due to nuclear and/or gravitational interactions) overcome the energy sinks (radiative and/or neutrino energy losses). When this condition is no more fulfilled, stars stop to evolve and a degenerate core forms in their interiors. The physical processes that determine the final mass of the stellar core will be described in some details as well as the consequent outcome (core collapse, thermonuclear explosions, formation of compact remnants). The state-of-the-art theoretical and experimental studies that contribute to our understanding of stellar evolution will be reviewed.

Advances in nuclear astrophysics with direct and indirect methods at IFIN-HH

L. Trache[1]

[1] *IFIN-HH Bucharest*

I will present results of doing nuclear astrophysics research in IFIN-HH Bucharest-Magurele in the last 2-3 years. There is progress on the two basic types of experimental activities:

- Direct measurements at low and very low energies with beams from the local 3 MV tandetron accelerator. We proved it competitive for measurements down into the Gamow window of reactions induced by light ions and alphas. Extra sensitivity is provided by the ultra-low background laboratory in a salt mine about 120 km away.
- Indirect measurements done with beams at international facilities with radioactive beams.

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

The Trojan Horse Method in Nuclear Astrophysics

A. Tumino[1,2]

[1] *Facoltá di Ingegneria e Architettura, Universitá degli Studi di Enna "Kore", Enna, Italy*
[2] *INFN - Laboratori Nazionali del Sud, Catania, Italy*

Understanding energy production and nucleosynthesis in stars requires a precise knowledge of the nuclear reaction rates at the energies of interest. To overcome the experimental difficulties arising from the small cross sections at those energies and from the presence of the electron screening, the Trojan Horse Method has been introduced. The method represents one of the most powerful tools for experimental nuclear astrophysics because of its advantage to measure unscreened low-energy cross sections of reactions between charged particles, and to retrieve information on the electron screening potential when direct measurements at ultra-low energies are available. This is done by selecting the quasi-free (QF) contribution of an appropriate three-body reaction $A+a \rightarrow c+C+s$, where a is described in terms of clusters $x \oplus s$. The QF reaction is performed at energies well above the Coulomb barrier, such that cluster x is brought already in the nuclear field of A, leaving s as spectator to the $A+x$ interaction. The THM has been successfully applied to several reactions connected with fundamental astrophysical problems as well as with industrial energy production. I will recall the basic ideas of the THM and show some recent results.

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Experimental approaches for nuclear astrophysical reactions with radioactive species

P.J. Woods[1]

[1] *University of Edinburgh*

The lectures will explore a range of different experimental approaches to constraining key nuclear properties and reaction rates of radioactive nuclei in astrophysical scenarios such as novae, supernovae, and massive stars.
There will consideration of how the radioactive species are produced and examples of new techniques, for example using heavy ion storage rings.

Seminars

Proton-Induced Reactions of ^{6}Li and ^{7}Be and their Importance in Nuclear Astrophysics

T. Chillery[1]

[1] *University of Edinburgh*

Proton-induced reactions on ^{6}Li and ^{7}Be play an important role in nuclear astrophysics studies related to primordial lithium abundances and solar neutrinos respectively. Predictions from Big Bang Nucleosynthesis (BBN) theory and Wilkinson Microwave Anisotropy Probe (WMAP) measurements make accurate predictions to cosmological light-element abundances. Whilst BBN forbids the existence of primordial ^{6}Li, the ^{6}Li/^{7}Li abundance ratio measured in pre-main sequence (PMS) stars is ~ 0.5. The ^{6}Li(p,α)^{3}He and ^{6}Li(p,γ)^{7}Be reactions are the main processes that contribute to ^{6}Li destruction in stars. Improvements on their low-energy S-factor values, including a search for a recently observed ^{6}Li(p,γ)^{7}Be low energy resonance, could help address the ^{6}Li abundance puzzle. An experimental investigation of both reactions was recently undertaken at LUNA. I will introduce the LUNA accelerator and present preliminary results of the ongoing analysis.

Recent Earth-bound experiments measuring solar neutrino fluxes from the Sun show discrepancies between both within each other and with the standard solar model (SSM). Of the reactions involved in the production of solar neutrinos, the ^{7}Be(p,γ)^{8}B still carries the largest uncertainties. To further constrain its S-factor at relevant energies, a precise study of the ^{7}Be(p,p)^{7}Be elastic scattering will be carried out at CIRCE (Centre for Isotopic Research on Cultural and Environmental heritage) in Caserta, Italy. Data will help to constrain the ^{7}Be(p,γ)^{8}B reaction cross section through a global R-matrix analysis. The ultimate drive of this effort in understanding the neutrino discrepancies is to use the Sun as a standard in the comparison to other stars across the Universe. In my talk I will provide a brief description of the CIRCE accelerator and present an update of the work carried out so far.

Improved measurements on the ^{10}B(p,α_0) ^{7}Be cross section using the Trojan Horse Method

A. Cvetinović[1], C. Spitaleri[1,2], R. Spartá[1], G. G. Rapisarda[1,2], S. M. Puglia[1], M. La Cognata[1], L. Lamia[2], R. G. Pizzone[1], S. Romano[1,2], M. L. Sergi[1]

[1] *INFN-Laboratori Nazionali del Sud, Catania, Italy*
[2] *Dipartimento di Fisica e Astronomia, University of Catania, Catania, Italy.*

The investigation of the ^{10}B(p,α)^{7}Be reaction at energies below the Coulomb barrier is motivated by several aspects. The biggest interest for this reaction has applied nuclear physics. During last few years the ^{11}B(p,2α)^{4}He reaction has being considered as a prime candidate for clean (aneutronic) fusion [1, 2] due to high Q-value and the absence of neutrons. Beside high natural abundance and its inexpensiveness, the main advantage of ^{11}B in the usage as a fusion fuel is also the lack of long-lived radioactive reaction products [3]. But due to the 20% ^{10}B in natural boron, production of ^{7}Be (T1/2=53.22±0.06 d) as a radioactive waste could represent a radiation-safety problem. From the standpoint of nuclear astrophysics, the ^{10}B(p,α)^{7}Be reaction plays the key role in prediction of boron abundance in stars because the ^{10}B burning process mostly proceeds via the (p,α) reaction. This reaction can be used as probe for internal stellar structure since depletion of light elements such as Li, Be and B occurs at different depths, therefore analysis of the resulting atmospheric abundances of these elements can help in understanding and confining the mixing processes [4 - 6].

The Trojan Horse Method (THM) has been applied to the quasi-free ^{2}H(^{10}B,α_0 ^{7}Be)n reaction induced at a boron-beam energy of 28 MeV. The astrophysical S-factor of the ^{10}B(p,α_0)^{7}Be reaction has been measured in a wide energy range, from 0 to 2.2 MeV. Selected experimental set-up ensured good separation between events populating the ^{7}Be ground and first exited state. In order to obtain the THM bare-nucleus astrophysical S-factor in absolute units, a normalization to the direct data has been performed and a value for electron screening potential of U_e=29559 eV has been extracted. Good agreement, within the experimental uncertainties, with the adiabatic limit of 340 eV has been found.

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The ^{19}F(α,p)^{22}Ne and ^{23}Na(p,α)^{20}Ne reaction in AGB nucleosynthesis via THM

G. D'Agata[1,2], R.G. Pizzone [1], C. Spitaleri[1], S. Blagus[3], V. Burjan[4], S. Cherubini[1,2], A. Di Pietro[1], P. Figuera[1], L. Grassi[3], G.L. Guardo[1], M. Gulino[1,5], S. Hayakawa[6], I. Indelicato[1], R. Kshetri[1,7], M. La Cognata[1], M. La Commara[8,9], L. Lamia[1], M. Lattuada[1,2], M. Mazzocco[10,11], T. Mijatoviċ[3], M. Milin[12], D. Miljaniċ[3,†], J. Mrazek[4], S. Palmerini[13,14], C. Parascandolo[8], D. Pierroutsakou[10], L. Prepolec[3], S.M.R. Puglia[1], G.G. Rapisarda[1], S. Romano[1,2], M.L. Sergi[1], N. Skukan[3], N. Soiċ[3], E. Strano[10,11], V. Tokiċ[3], O. Trippella[13,14], A. Tumino[1,5], M. Uroiċ[3], D. Vescovi[13,14]

[1] *INFN-Laboratori Nazionali del Sud, via S. Sofia, 095123, Catania, Italy*
[2] *Dipartimento di Fisica e Astronomia, Universitá degi studi di Catania, via Santa Sofia 64, 95123, Catania, Italy*
[3] *Ruđer Bošković Institute, Bijenicka cesta, 54, 10000, Zagreb, HR*
[4] *Institute for Nuclear Physics, Prague- Řež, Czech Republic*
[5] *Facoltá di Ingegneria ed Architettura, Kore University, Viale delle Olimpiadi, 1, I-94100 Enna, Italy*
[6] *Center for Nuclear Study, the University of Tokyo, RIKEN campus, 2-1 Hirosawa, Wako, 351-0198, Japan*
[7] *Department of Physics, Sidho-Kanho-Birsha University, Purulia - 723104, WB, India*
[8] *INFN, Sezione di Napoli, via Cintia, 80216 Napoli, Italy*
[9] *Dipartimento di Scienze Fisiche, Universitá di Napoli Federico II, via Cintia, I-80126*
[10] *INFN, Sezione di Padova, via Marzolo 8, I-35131 Padova, Italy*
[11] *INFN, Sezione di Padova, via Marzolo 8, I-35131 Padova, Italy*
[12] *Department of Physics, University of Zagreb, Bijenicka 32, Zagreb, Croatia*
[13] *Dipartimento di Fisica, Universitá di Perugia, via A. Pascoli, I-06123 Perugia, Italy*
[14] *INFN, Sezione di Perugia, via A. Pascoli, I-06123 Perugia, Italy*

Fluorine abundance in the universe is far from being reproduced by models. In particular, it is strongly underestimated with respect to what experimentally observed in AGB-stars, considered to be the main production sites for 19F, the only stable isotope of Fluorine. AGB-stars are composed by a degenerate CO core surrounded by a He and a H shell. Those shells are then divided by a "thin" layer ($10^{-2}\div103$ $R_\odot$). If temperature is T$\approx10^8$K, the ^{14}N produced in the CNO cycle can be processed into ^{19}F by the chain of reactions ^{14}N(α, γ)^{18}F($\beta^+\nu$)^{18}N(p,γ)^{19}F. If the production pattern of ^{19}F is quite clear, the same thing can not be said for its destruction pathways. In AGB-environment two reactions are considered to be the main destructions pattern for ^{19}F: ^{19}F(p,α)^{16}O[1] and ^{19}F(α,p)^{22}Ne. We focused on this second reaction (results published in [2][6]): try to obtain informations about this reaction is, indeed, very difficult with direct nuclear physics experiments. That is due to the Coulomb barrier, that strongly reduces the cross-section (to some pico-nanobarn). The direct measurements of the ^{19}F(α,p)^{22}Ne reaction at lowest energy [3][4] is at E_{CM}=0.91 MeV. However, given the typical temperatures for a low-mass AGB-stars (2×10^8K, $2\div4$ $M_\odot$), the Gamow window for this reaction is between 390 and 800 keV. For cases like that, in the last 20 years indirect methods have been used. Among these, the Trojan Horse Method is one of the most important for astrophysical measurements [5]. For these reasons we decided perform an experiment at Rudjer Boskovic Institut (Zagreb), that consisted in using a 6Li beam to investigate the two body reaction ^{19}F(α,p)^{22}Ne using the ^{6}Li(^{19}F,p ^{22}Ne)^{2}H three-body one. In this why we were able the extract a cross-section in absolute unit, and to calculate the S(E)-factor and the reaction rate, and the astrophysical impact of this measure is in evaluation. In the end, some preliminary results of the study of the ^{23}Na(p,α)^{20}Ne via the ^{23}Na(d,p^{22}Ne)n using THM will also be discussed. The reaction ^{23}Na(p,α)^{20}Ne reaction is of primary importance for sodium destruction inside the nucleosynthesis path in the A>20 mass region in intermediate mass (4÷8 $M_{\odot}$) AGB-stars. This reaction is also involved in the branching point of the Ne-Na cycle, responsible for hydrogen burning at high temperatures (T=20÷100 T_6).

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^{7}Be(n,p) cross section measurement for the Cosmological Lithium Problem at the n_TOF facility at CERN

L.A. Damone[1]

[1] *INFN - Sez. Bari*

The primordial abundance of ^{7}Li predicted by models of the Big Bang Nucleosynthesis (BBN) is more than a factor 2 larger than observed in metal poor halo stars. This discrepancy, referred to as the Cosmological Lithium Problem (CLiP), is one of the most puzzling problems in Nuclear Astrophysics. The abundance of ^{7}Li is essentially linked to the production and destruction of ^{7}Be. While the main reactions of the ^{7}Be production are relatively well known, the same cannot be said about the reactions responsible for its destruction. Several measurements have excluded a significant impact on the CLiP of charged particle induced reactions on ^{7}Be. As for neutron induced reactions, a recent measurement at n_TOF has also ruled out a possible contribution of the (n,α) reaction to the solution of the problem, while there is still the possibility that the (n,p) reaction could play an important role. Despite of the importance of this reaction in BBN, there is a lack of cross section data. Taking advantage of the innovative features of the second experimental area at the n_TOF facility at CERN, e.g. the very high instantaneous neutron flux, the wide energy range and the low background conditions, an accurate measurement of ^{7}Be(n,p) cross section has been recently performed at n_TOF, with a pure ^{7}Be target produced by implantation of a ^{7}Be beam at ISOLDE. The experimental procedure and setup used in the measurement and the results obtained so far will be here presented.

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High precision investigation of the fully sequential decay width of the Hoyle state in ^{12}C

D. Dell'Aquila[1,2], I. Lombardo[1,2], G. Verde[3], M. Vigilante[1,2], L.A. Acosta Sanchez[4], C. Agodi[5], F. Cappuzello[5,6], D. Carbone[5], M. Cavallaro[5], S. Cherubini[5,6], A. vetinović[5], G. D'Agata[5,6], L. Francalanza[2], G.L. Guardo[5], M. Gulino[5,7], I. Indelicato[5], M. L Cognata[5], L. Lamia[5], A. Ordine[2], R.G. Pizzone[5], S.M.R. Puglia[5], G.G. Rapisarda[5], S. Romano[5,6], G. Santagati[5], R. Spartá[5], G. Spadaccini[1,2], C. Spitaleri[5,6], A. Tumino[5,7]

[1] *Univ. Napoli Federico II - Napoli, Italy*
[2] *INFN- Sez. Napoli*
[3] *INFN- Sez. Catania*
[4] *National Autonomous University of Mexico*
[5] *INFN-LNS*
[6] *Dip. di Fisica e Astronomia, Universitá di Catania*
[7] *Facoltá di Ingegneria ed Architettura, Universitá Kore*

The structure of the Hoyle state in ^{12}C(7.654 MeV, 0+) is of crucial importance in Nuclear Structure and Nuclear Astrophysics. On the Nuclear Structure point of view, this state represents an interesting example of clustering in nuclei, having a well pronounced 3α nature. Anyway, the structure of this state is quite unusual and its study is extremely challenging [1]. In Nuclear Astrophysics, this state is involved in the triple-alpha process in stars. The nucleosynthesis of carbon during the helium burning proceeds indeed exclusively via this resonance in ^{12}C. To evaluate the reaction rate of such a process in astrophysical scenarios that burn helium at temperatures lower than 0.1 GK, it is however important to know precisely its direct decay partial width [2]. Recently, Raduta et al. [3] reported a significant contribution of direct emission of 3 alphas (17% 5.0%) in the decay of the Hoyle state, in constrast with [4], which would result in an increase of several orders of magnitude in the calculated 3α reaction rate at low temperatures. This result was then contradicted in more recent investigations [5,6,7]. Anyway, while Rana et al. [6] suggest a non-vanishing contribution of this process (0.91% 0.14%), Kirsebom et al. [5] and Itoh et al. [7] report no evidence of this process, indicating an upper limit of, respectively, 0.4% (C.L 99.5%) and 0.2% (95%). The existence of a direct decay in 3α of the Hoyle state represents, therefore, a still open problem in Nuclear Structure and Nuclear Astrophysics. We developed a specific experiment with the aim to increase the sensitivity to such a process: the HOYLE (Hodoscope Oriented Yield Loader Experiment) experiment at INFN-LNS. The basic idea of our investigation is to use the ^{14}N(d,α) reaction with an anti-coincidence telescope to identify alpha particles associated with the residual ^{12}C* nucleus in the Hoyle state and to reconstruct the corresponding 3 particle decay of ^{12}C* with a hodoscope. In our experiment, we obtained, for the first time, very high statistics and a quasi-zero background level. We infer no indication of a 3α direct decay with unprecedented precision.

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First Measurement of the Stellar ^{72}Ge(n,γ) Cross Section

M. Dietz[1], C. Lederer-Woods[1]

[1] *School of Physics and Astronomy, University of Edinburgh, United Kingdom*

The slow neutron capture process (s-process) is responsible for producing about half of the elemental abundances heavier than iron in the universe. Neutron capture cross sections on stable isotopes are a key nuclear physics input for s-process studies. The neutron capture cross section of ^{72}Ge was measured at n_TOF (CERN) for the first time at stellar energies, as part of an experimental campaign to measure neutron capture on all stable isotopes of Ge. The ^{72}Ge(n,γ) cross section has an important influence on production of isotopes between Ge and Zr in the s-process in massive stars and therefore experimental data are urgently required. n_TOF is a neutron time-of-flight facility at CERN. Neutrons over a large energy range (25 MeV to several GeV) are produced by spallation reactions of a highly energetic (20 GeV), pulsed proton beam impinging on a massive Pb target. The measurement was performed using an enriched $^{72}GeO_2$ sample at a distance of 185 m from the spallation target (Experimental Area 1), which allows a measurement with high neutron energy resolution. The prompt gamma rays produced after neutron capture were detected with a set of liquid scintillation detectors (C_6D_6). The motivation, experiment and current status of the data analysis will be presented.

Development of the ELISSA array: the prototype of Laboratori Nazionali del Sud

G.L. Guardo[1], A. Anzalone[2], D.L. Balabanski[1], S. Chesnevskaya[1], V. Crucillá[2], M. Gulino[2,3], M. La Cognata[2], D. Lattuada[1], C. Matei[1], R.G. Pizzone[2], G.G. Rapisarda[2], S. Romano[2,4], C. Spitaleri[2], A. Taffara[2], A. Tumino[2,3], Y. Xu[1]

[1] *ELI-NP/ IFIN-HH, 30 Reactorului Street, 077125 Magurele, Romania*
[2] *INFN, Laboratori Nazionali del Sud, Via Santa Sofia 62, 95123 Catania, Italy*
[3] *Facoltá di Ingegneria e Architettura, Universitá Kore, Enna, Italy*
[4] *Dipartimento di Fisica e Astronomia, Universitá degli Studi, Via Santa Sofia 64, 95123 Catania, Italy*

The Extreme Light Infrastructure - Nuclear Physics (ELI-NP) facility, under construction in Magurele near Bucharest in Romania, will provide high-intensity and high-resolution gamma ray beams that can be used to address hotly debated problems in nuclear astrophysics, such as the measurement of controversial ^{12}C(α,γ)^{16}O cross section through the ^{16}O(γ,α)^{12}C reaction, the accurate measurements of the cross sections of the ^{24}Mg(γ,α)^{20}Ne reaction and other photo-dissociation processes relevant to stellar evolution and nucleosynthesis [1].
For this purpose, a silicon strip detector array (named ELISSA) will be realized in a common effort by ELI-NP and Laboratori Nazionali del Sud (INFN-LNS) (Catania, Italy), in order to measure excitation functions and angular distributions over a wide energy and angular range. According to our simulations, the final design of ELISSA will be a very compact barrel configuration, leaving open the possibility in the future to pair a neutron detector with the array. The kinematical identification will allow to separate the reaction of interest from others thanks to the good expected angular and energy resolutions.
A prototype of ELISSA was built and tested at INFN-LNS in Catania with the support of ELI-NP. In this occasion, we have carried out experiments with alpha sources and with a 11 MeV ^{7}Li beam. We used X3 and QQQ3 silicon-strip position sensitive detectors manufactured by Micron Semiconductor ltd. Thanks to our approach, the first results of those tests show up a very good energy resolution (better than 1%) and very good position resolution, of the order of 1 mm. At very low energies, below 1 MeV, a worse position resolution is found, of the order of 5 mm, but still good enough for the measurement of angular distribution and the kinematical identification of the reactions induced on the target by gamma beams. Moreover, a threshold of 150 keV can be easily achieved with no cooling. We will discuss technical details of the detector and present results regarding Monte Carlo simulation, energy resolution and detection thresholds of ELISSA, the physical cases to be investigated.
To sum up, these tests allow us to say that the X3 detectors, as well the standard QQQ3 detectors, are perfectly suited for nuclear astrophysics studies with ELISSA.

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Commissioning of the new Texas Active Target Detector

J. Hooker[1], G. Rogachev[2], Y. Koshchiy[3], E. Uberseder[3], E. Pollacco[4], C. Hunt[3], H. Jayatissa[3], S. Upadhyayula[1]

[1] *Texas A&M University - Cyclotron Institute*
[2] *Florida State University*
[3] *Texas A&M University*
[4] *CEA - Saclay*

The Texas Active Target (TexAT) detector is a general purpose active target detector at the Cyclotron Institute at Texas A&M University. It is designed to study low energy nuclear structure and astrophysics with rare isotope beams by the MARS spectrometer or the new reaccelerated beam facility at the Cyclotron Institute such as ^{23}Al(p,p) and relavent (α,p) reactions. The TexAT detector is a time projection chamber consisting of a MicroMegas plane with CsI(Ti)-backed silicon detectors which allows tracking for the incoming beam particles and recoils for high resolution experiments. The first run with TexAT will be in August 2017 measuring ^{12}C+p scattering and the results of this test will be presented.

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Study of the contribution of the ^{7}Be(d, p) reaction to the ^{7}Li problem in the Big-Bang Nucleosynthesis

A. Inoue[1]

[1] *Research Center for Nuclear Physics, Osaka University*

Our research purpose is to measure the ^{7}Be(d, p) reaction to solve the ^{7}Li problem in the Big-Bang Nucleosynthesis (BBN). The ^{7}Li problem is an overestimation of the primordial ^{7}Li abundance in the standard BBN model. A recent theoretical BBN model predicts a primordial ^{7}Li abundance that is 3 times larger than the recent precise observation [1]. The difference is quite large while the abundance of the other light nuclei are reproduced well. This is one of the biggest problems in the BBN models and this illustrates the gaps in knowledge of the processes of the primordial formation of our universe.

Light nuclei were produced up to ^{7}Be by nuclear reactions in several hundred seconds following the Big Bang. ^{7}Li nuclei were considered to be predominantly produced by the β decay of ^{7}Be in the standard BBN model. The β decay half life of ^{7}Be, 5 million seconds, is much longer than the production of light nuclei after the Big Bang. Thus, one possible scenario to solve the ^{7}Li problem is that ^{7}Be was destructed in the time scale of the nuclear reactions.

The ^{7}Be$(d,p)^8$Be and the ^{7}Be(n, α)^{4}He reactions are two promising processes of destructing ^{7}Be. We focus on the ^{7}Be(d, p)^{8}Be reaction since the contribution from ^{7}Be(d, p)^{8}Be is suggested to be larger than ^{7}Be(n, α)^{4}He [2], [3].

We plan to measure the cross section of the ^{7}Be(d, p)^{8}Be reaction in the BBN energy region of 100 - 400 keV. The available data are insufficient in the accuracy or in the energy range [4], [5]. We are developing an unstable ^{7}Be target for the measurement of the ^{7}Be(d, p)^{8}Be reaction with high incident-energy resolution in normal kinematics. The development of the unstable target is a big technical challenge. We apply the *Implantation method*; ^{7}Be particles are implanted by irradiating a gold host target with a ^{7}Be beam.

We performed an experiment to produce a ^{7}Be implanted target at CRIB, Center for Nuclear Study (CNS), University of Tokyo, in June 2016. The primary beam was ^{7}Li^{2+} at 5.6 MeV/nucleon. The secondary beam was produced by the ^{1}H(^{7}Li, ^{7}Be) reaction. The secondary beam energy was 4.0 MeV/nucleon. The ^{7}Be beam irradiated a 10 μm thick gold foil as a host material after an energy degrader made of gold with a thickness of 15 μm and 2 mmϕ collimator.

We measured the amount of the implanted ^{7}Be by detecting 477 keV γ rays with a LaBr$_3$ detector after the implantation. The γ ray is emitted in the electron capture decay process of ^{7}Be with a branching ratio of 10.4%. We obtained 1.3×10^{11} ^{7}Be particles after 19 hours of irradiation.

We also performed a development experiment at CRIB in May 2017. We achieved 1.2×10^{12} ^{7}Be particles after the optimization of the magnets setup and setting of beam-line optics. As a next step, we plan to measure the ^{7}Be(d, p) reaction. The experiment is planned for 2018 at JAEA.

The progress of the development and the preparation status will be presented.

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The study of the ^{22}Ne(α,n)^{25}Mg reaction rate via indirect sub-coulomb alpha-transfer techniques

H. Jayatissa[1], G. Rogachev[1], E. Uberseder[2], Y. Koshchiy[1], O. Trippella[3], J. Hooker[1], S. Upadhyayula[1], C. Magana[2], C. Hunt[1], V. Goldberg[1], B. Roeder[1], A. Saastamoinen[1], A. Spiridon[1],M. Dag[1]

[1] *Cyclotron Institute, Texas A&M University*
[2] *Texas A&M University*
[3] *Universitá di Perugia*

The ^{222}Ne(α,n) reaction is a very important neutron source reaction for the slow neutron capture process (s-process) in asymptotic giant branch stars. These direct measurements are very difficult to carry out at the energy regimes of interest for astrophysics (Gamow energies) due to the extremely small reaction cross section. The large uncertainties introduced when extrapolating direct measurements at high energies down to the Gamow energies can be overcome by measuring the Asymptotic Normalization Coefficients (ANC) of the relevant states using alpha-transfer reactions at sub-Coulomb energies to reduce the model dependence. The study of the ^{22}Ne(^{6}Li,d) and ^{22}Ne(^{7}Li,t) reaction was carried out at the Cyclotron Institute at Texas A&M University. The alpha-ANC measurements for the near alpha-threshold resonances of ^{26}Mg provide constraints for the ^{22}Ne(α,n) reaction rate. The effect of this reaction rate on the final abundances of the s-process isotopes will be discussed.

Spectroscopy of nuclei ^{23}Mg with interest for Nuclear Astrophyscis

A. Lara[1],V. Guimarães[1],Marlete Assunção [2], F. Hammache[3], N. de Sereville[3], I. Stefan[3], M. Assie[3], F. Flavigny[3], A. Gottardo[3], A. Lefebvre-Schuhl[3], A. Meyer[3], C. Portail[3], M. Maccormick[3], A. Coc[3], V. Tadischef[3], J. Kiener[3], L. Perrot[3],F. de Oliveira[4], C. Michelagnoli[4]

[1] *Instituto de Física, Universidade de São Paulo, São Paulo, Brazil*
[2] *Departamento de Física, Universidade Federal de São Paulo, São Paulo, Brazil*
[3] *Institut de Physique Nucléaire, Orsay, France*
[4] *Ganil, Caen, France*

The knowledge of the nuclear reactions that take place inside the stars allows to discuss what will be the evolution of astro and the relation of abundance between isotopes. In many cases the detection of trace elements originating from certain reactions is used to infer the occurrence of extreme events, such as new and supernovae. One of these elements is the ^{22}Na, whose abundance depends on proton capture, by the ^{22}Na(p,γ)^{23}Mg reaction. Its presence is the event signature type nova . However, this reaction is dominated by resonances of dificult detect, as reported in other works of the literature in the area. With this motivation, an experiment neutron transfer was carried out in the last year by the reaction of ^{24}Mg(^{4}He,^{3}He)^{23}Mg in the Orsay-Tandem- Alto (France) with the Enge Split-Pole spectrometer. In this experiment two targets were used: ^{24}Mg isolated and another composed of stable isotopes of magnesium (^{24}Mg 80%, ^{23}Mg 10% and ^{25}Mg 10%), which were bombarded of alpha particles with energy of 25 MeV. The ^{23}Mg states were analyzed by the energy of the ^{3}He ejetcted of this reaction, deflecteds by the action of a magnetic field of approximately 1 T, and detected by system composite by E-E and a position-sensitive gas detector. The proposal then is to present the obtained spectra for different angles of detection and the respecty angular distribution. These results are important in determining the energy of some resonances and determining the parameters of these states, such as spin and the spectroscopic factor.

Geant4 simulations and photonuclear astrophysics at ELI-NP

D. Lattuada[1], A. Anzalone[2], D.L. Balabanski[1], S. Chesnevskaya[1], V. Crucillà[2], G.L. Guardo[1], M. Gulino[2,3] , M. La Cognata[2], C. Matei[1], R.G. Pizzone[2], G.G. Rapisarda[2], S. Romano[2,4], C. Spitaleri[2], A. Tumino[2,3], Y. Xu[1]

[1] *ELI-NP / IFIN-HH, 30 Reactorului Street, 077125 Magurele, Romania*
[2] *INFN, Laboratori Nazionali del Sud, Catania, Italy*
[3] *Facoltà di Ingegneria e Architettura, Università Kore, Enna, Italy*
[3] *Dipartimento di Fisica e Astronomia, Università degli Studi, Catania, Italy*

Photonuclear reactions near threshold energies are of great interest in nuclear astrophysics. Present and future gamma-beam facilities represent a great opportunity to validate and evaluate the cross-sections of many nuclear reactions at near-threshold energies, whose data mostly come from theoretical calculations. Monte Carlo (MC) simulations are very important in order to evaluate the reaction rates and to maximize the detection efficiency by suggesting improvements for the detector setup, thus they become mandatory at R&D and preparatory stages of any nuclear physics experiment. We developed a software that exploits the validated tracking GEANT4[1] libraries and the simple and widely used event generator of the ROOT[2] libraries to provide a fast and realiable MC tool to be used for photonuclear reactions. This tool is intended to be used for ELISSA (ELI Silicon Strip Array), a new silicon-strip detector array under development at the Extreme Light Infrastructure - Nuclear Physics (ELI-NP[3]) facility, but it aims to become an instrument to be used by any user at ELI-NP facility since any detector geometry and any nuclear reaction can be studied. We examine some case-study experiments and we discuss the results of the MC simulations performed in order to evaluate the effects of the straggling of the exit particles due to the thickness of the target and of the resolution of the silicon detectors.

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The investigation of quasi-free scattering reactions with the two-proton-halo nucleus ^{17}Ne

C. Lehr[1], T. Aumann[1], F. Wamers[1]

[1] *Technical University Darmstadt*

^{17}Ne is a Borromean two-proton-halo nucleus located at the proton- dripline and therefore an interesting candidate for nuclear-structure studies. Reactions of the nucleus ^{17}Ne have been measured in complete kinematics at the R3B/LAND setup at GSI in Darmstadt. The experimental method is based on exclusive measurements of one-proton-removal reactions. Polyethylene (CH_2) and carbon (C) were used as targets. Thus it is possible to reconstruct the pure hydrogen (H) contribution of the CH_2 data by subtracting the carbon background. The resulting events are clean quasi-free-scattering (p,2p) reactions showing the typical angular correlations known from p-p scattering. Thereby quasi-free (p,2p) and carbon-induced one-proton removal reactions are studied separately. Quasi-free-scattering reactions are compared with carbon-induced one-proton removal reactions and shown to be a clean tool for nuclear- structure studies.

This work is supported by HIC for FAIR, the GSI-TU Darmstadt cooperation and the BMBF project 05P15RDFN1.

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How can the Lithium problem be resolved?

T. Makki[1]

[1] *???????????????*

The standard Big Bang nucleosynthesis (SBBN) is a nice theory that explains the formation of light elements in the universe during the first three minutes. The observed abundances of light elements are in good agreement for all produced elements except for Lithium (^7Li). The situation concerningits abundance became very complicated because of the significant discrepancy between observations as obtained from metal poor halo starsand the predictions of SBBN supported by WMAP data.In addition, these observations are not conforming the well-knownspite plateau down to metallicitylower than $\left[\frac{Fe}{H}\right]$ = -3.0. Consequently, no theory is perfect and one has a Lithium problem.

Attempting to resolve this Lithium problem seems to be a complex task because of no single answer can be extracted. Many attempts to resolve this problem on purely astrophysical and nuclear physics ground were not successful. In this talk we will discusspossible solutions concerning the revised nuclear reactions like the new measured $^7Be(n,\alpha)^4He$ by Barbagallo, M. et al.(2016) and $^7Be(e^-,\nu_e)^7Li$.

Furthermore, it seems that resolving the Lithium problem needs non- standard aspects such as neutrinos properties (varying chemical potentials, number, and temperature) and adding dark energy and dark entropy components. Adding these components, we found a way to reduce the Lithium abundance from the level predicted by SBBN.

Lifetime Measurement of Higher-Lying Excited States in ^{16}C

Michael Mathy[1] and Marina Petri[2,1]

[1] *Institut für Kernphysik, TU Darmstadt, Germany*
[2] *Department of Physics, University of York, United Kingdom*

Electromagnetic properties of the neutron-rich carbon isotopes provide an exciting opportunity to directly test theoretical models using NN+3N Hamiltonians derived from chiral EFT. Indeed, the EM properties of ^{16}C are particularly sensitive to the inclusion of 3N forces in the calculations [1]. However, the experimental information on ^{16}C are limited to the lifetime of the first excited state and an upper limit of 4 ps for the higher-lying states [2,3]. To investigate lifetimes and branching ratios of the higher-lying states (2_2^+, 3^+, 4^+) a fusion-evaporation reaction has been performed at the Argonne National Laboratory. Evaporated charged particles were identified using the μ-Ball detector and emitted gamma rays were identified using the Gammasphere array. Lifetimes of the excited states can be extracted using the doppler shift attenuation method. In the talk the measurement techniques and preliminary gamma spectra of ^{16}C, which can be used to give a first approximation of the magnitude of the lifetime, will be presented. Also ideas for further analysis methods using realtistic Geant4 simulations will be outlined. This work was supported by the DFG under contract No. SFB 1245 and The Royal Society.

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Study of key resonances in the ^{30}P(p,γ)^{31}S reaction in classical novae

A. Meyer[1], N. De Sereville [1,2], F. Hammache[1], P. Adsley[1]

[1] *Institut de Physique Nucléaire d'Orsay*
[2] *CNRS*

Classical novae outbursts are the third most energetic explosions in the Universe after gamma-ray bursts and supernovae. During this explosive burning, nucleosynthesis takes place and the newly synthesized material is ejected into the interstellar medium. In order to understand these objects, the study of presolar grains and -ray emitters are of specific interest since they can give direct insights into the nucleosynthesis processes and isotopic abundances.

The ^{30}P(p,γ)^{31}S reaction is one of the few remaining reactions which rate uncertainty has a strong impact on classical novae model predictions. Sensitivity studies have shown that it has the largest impact on the predicted elemental abundance ratios of Si/H, O/S, S/Al, O/P and P/Al which can be used to constrain physical properties of classical novae. The ^{30}Si/^{28}Si isotopic ratio, which is an important signature that helps to identify presolar meteoritic grains of a likely nova origin, depends also strongly on the ^{30}P(p,γ)^{31}S reaction rate.

To reduce the nuclear uncertainties associated to this reaction we performed an experiment at the ALTO facility of Orsay using the ^{31}P(^{3}He,t)^{31}S reaction to populate ^{31}S excited states of astrophysical interest. The tritons were momentum analysed using the Enge Split-Pole magnetic spectrometer and the decaying protons were detected in coincidence in an array of six DSSSDs (Double Sided Silicon Stripped Detectors). The comparison of the focal plane spectra obtained for single and coincidence events will allow the extraction of the proton branching ratios needed to calculate ^{30}P(p,γ)^{31}S reaction rate.

After a presentation of the astrophysical context of this work, the current situation of the ^{30}P(p,γ)^{31}S reaction rate will be discussed. The Orsay experiment will be described and the analysis of the single events from the Split-Pole focal plane detector will be presented.

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Resonance Effects in Carbon Burning Process on Type Ia Supernovae

K. Mori[1], M. Famiano[2], T. Kajino[1,3],

[1] *National Astronomical Observatory of Japan*
[2] *Western Michigan University*
[3] *The University of Tokyo*

Type Ia supernovae (SNe Ia) are thought to be thermonuclear explosion of white dwarfs (WDs). Their progenitor is not understood well. One popular scenario is the single degenerate (SD) scenario, in which mass accretes on the WD and it explodes as a supernova when it grows to Chandrasekhar mass. Another scenario is the double degenerate scenario, which attributes SNe Ia to WD-WD binary mergers. In the SD scenario, the WD becomes convective due to the ^{12}C+^{12}C reaction just before the SN Ia explosion. This evolutionary step is called carbon simmering and changes electron fraction through electron capture reactions. This will change following explosive nucleosynthesis. In the DD scenario, the fate of the WD-WD merger depends on the reaction rate of ^{12}C+^{12}C reaction.

In this way, the ^{12}C+^{12}C reaction is an important process in astrophysics. Therefore, the cross section of this reaction in the low energy region is being measured by several groups now. In this talk, we assume a low energy resonance using the Breit-Wigner formula and calculate the reaction rate. This rate is applied to the both scenarios of SNe Ia progenitors and its astrophysical implication is discussed.

Radiation-hydrodynamical modelling of post-explosive phases of core-collapse supernovaet

M.L. Pumo[1,2,3]

[1] *Universitá di Catania*
[2] *INFN - LNS*
[3] *INAF-OAPd*

It is widely accepted that core-collapse supernovae (CC-SNe) represent the final explosive evolutionary phase of stars having initial masses larger than 8-10 solar masses (e.g. [1] and [2]). In addition to their intrinsic interest, CC-SNe are relevant to many astrophysical issues associated, for example, with the nucleosynthesis of intermediate and trans-iron elements, the physical and chemical evolution of the environments where they take place, the production of dust, the detection of gravitational waves, and the construction of Hubble diagrams.

In spite of the importance of these explosive events in different branches of modern astrophysics and, more generally, of modern physics, ranging from cosmology to nuclear physics, there are still several open questions to be answered, linked to the "extreme variety" of their spectrophotometric behaviors and related to the uncertainties in their modelling (see e.g. [3], [4] and references therein).

We will address some of these open issues, paying attention also to the sophisticated numerical computational tools to be developed for tackling such very challenging problems.

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X-ray burst studies with the JENSA gas jet target

K. Schmidt[1,2]
for the JENSA collaboration

[1] *National Superconducting Cyclotron Laboratory, East Lansing, MI, USA*
[2] *Joint Institute for Nuclear Astrophysics - Center for the Evolution of the Elements, East Lansing, MI, USA*

Contact email: *schmidtk@nscl.msu.edu*

When a neutron star accretes hydrogen and helium from the outer layers of its companion star, thermonuclear burning enables the αp-process as a break out mechanism from the hot CNO cycle. Model calculations predict (α, p) reaction rates to significantly affect light curves and elemental abundances in the burst ashes.

The Jet Experiments in Nuclear Structure and Astrophysics (JENSA) gas jet target enables the direct measurement of previously inaccessible (α,p) reactions with radioactive beams provided by the rare isotope re-accelerator ReA3 at the National Superconducting Cyclotron Laboratory (NSCL), USA. JENSA is going to be the main target for the Recoil Separator for Capture Reactions (SECAR) at the Facility of Rare Isotope Beams (FRIB). Commissioning of JENSA and first experiments at Oak Ridge National Laboratory (ORNL) showed a highly localized, pure gas target with a density of $\sim 10^{19}$ atoms per square centimeter.

Preliminary results will be presented from a commissioning experiment at NSCL studying the $^{14}\mathrm{N}(\alpha, \mathrm{p})^{17}\mathrm{O}$ reaction and from the first direct cross section measurement of the $^{34}\mathrm{Ar}(\alpha, \mathrm{p})^{37}\mathrm{K}$ reaction.

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Isomeric ^{26}Al beam production with CRIB

H. Shimizu[1], D. Kahl[2], H. Yamaguchi[1], K. Abe[1], O. Beliuskina[1], S. M. Cha[3], K. Y. Chae[3], A. A. Chen[4], Z. Ge[5], S. Hayakawa[1], N. Imai[1], N. Iwasa[6], A. Kim[7], D. H. Kim[7], M. J. Kim[3], S. Kubono[5], M. S. Kwag[3], J. Liang[4], J. Y. Moon[8,9], S. Nishimura[5], S. Oka[10], S. Y. Park[7], A. Psaltis[4], T. Teranishi[10], Y. Ueno[10], and L. Yang[1]

[1] *Center for Nuclear Study, Graduate School of Science, the University of Tokyo*
[2] *School of Physics and Astronomy, the University of Edinburgh*
[3] *Department of Physics, Sungkyunkwan University*
[4] *Department of Physics and Astronomy, McMaster University*
[5] *RIKEN Nishina Center, RIKEN, Wako*
[6] *Department of Physics, Tohoku University*
[7] *Department of Physics, Ewha Womans University*
[8] *Institute for Basic Science*
[9] *Wako Nuclear Science Center*
[10] *Department of Physics, Kyushu University*

The galactic abundance of the ^{26}Al radio nuclide provides a unique window to the ongoing nucleosynthesis in the Milky Way. ^{26}Al is known as the first specific radioactivity detected that decays via its characteristic β-delayed γ-ray and it has been directry observed by astronomical telescopes. Despite a lot of effort over the past three decades, the particular production sites of galactic ^{26}Al are poorly understood and there may be a discrepancy between observations and theories on estimated abundance of ^{26}Al in the intersteller medium. This problem is complicated by its isomer, $^{26\mathrm{m}}$Al, which has low spin-parity $J^{\pi} = 0^{+}$ and short lifetime $T_{1/2} = 6.35$ s compared with ground state, $^{26\mathrm{g}}$Al, which is $J^{\pi} = 5^{+}$ and $T_{1/2} = 0.72$ Myr, and thus $^{26\mathrm{m}}$Al directly decays to stable state of ^{26}Mg without emitting γ-ray. Therefore, $^{26\mathrm{m}}$Al could not be detected from γ-ray observations, and moreover it is treated as separate species in nucleosynthesis models. However, these two states, $^{26\mathrm{g,m}}$Al, are suggested to be in transition and in thermal equilibrium by thermal photons, at least in extremely high temparature environments, such as a supernova. Although the isomeric state may play an important role to reduce the yield of ^{26}Al, the experimetnal imformation on the isomer is pooly examined and thus was requested for further experimental study by steller modelers.

We performed an experiment to measure proton elastic resonant scattering of a mixed $^{26\mathrm{m,g}}$Al with a thick target in inverse kinematics (TTIK) by using the Center for Nuclear Study low-energy radioactive ion beam separator (CRIB), located at RIKEN Nishina Center. It aimed to search for strong proton resonances and determine the partial width Γ_p with low spin-parity in ^{27}Si. We present the results of the RI beam production, diagnosis of the $^{26\mathrm{m}}$Al content of the beam by both γ-ray originating in annihilation and positron spectra detected in silicon detectors, as well as preliminary results on the proton scattering measurement.

Measurement ANCs of ^{26}Si(p,γ)^{27}P via mirror nucleus ^{26}Mg(d,p)

Ivan Sivek[1]

[1] *Nuclear Physics Institute of the ASCR, 25068 Rez, Czech Republic*

This reaction is interesting, since it has an impact on amount of observable galactic ^{26}Al. At the beginning differential cross section of ^{26}Mg(^{3}He,d)^{27}Al reaction was measured using ΔE-E method to obtain characteristics of unknown ^{26}Mg target. This target turned to be very inhomogeneous, so new targets had to be manufactured. Thank to experts in INFN-LNS we obtained a set of new perfect-quality targets, which were subject of most recent ^{26}Mg(d,p) measurement. Results obtained with both targets are compared.

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^{7}Be and ^{8}B reaction dynamics at Coulomb barrier energies

E.Strano[1,2], M.Mazzocco[1,2], A.Boiano[3], C.Boiano[4], M.La Commara[3,5], C.Manea[2], C.Parascandolo[3], D.Pierroutsakou[3], C.Signorini[6], D.Torresi[1,2], H.Yamaguchi[7], D.Kahl[7], L.Acosta[8,9], P.Di Meo[3], J.P.Fernandez-Garcia[9], T.Glodariu[10], J.Grebosz[11], A.Guglielmetti[4,12], N.Imai[7,13], Y.Hirayama[13], H.Ishiyama[13], N.Iwasa[14], S.C.Jeong[13,15], H.M.Jia[16], N.Keeley[17], Y.H.Kim[13], S.Kimura[13], S.Kubono[7,18], J.A.Lay[1,2], C.J.Lin[16], G.Marquinez-Duran[8], I.Martel[8], H.Miyatake[13], M.Mukai[13], T.Nakao[19], M.Nicoletto[2], A.Pakou[20], K.Rusek[21], Y.Sakaguchi[7], A.M.Sanchez-Benitez[8], T.Sava[10], O.Sgouros[20], C.Stefanini[1,2], F.Soramel[1,2], V.Soukeras[20], E.Stiliaris[22], L.Stroe[10], T.Teranishi[23], N.Toniolo[6], Y.Wakabayashi[18], Y.X.Watanabe[13], L.Yang[16], Y.Y.Yang[24]

[1] *Dipartimento di Fisica e Astronomia, Universit di Padova, Padova, Italy*
[2] *INFN-Sezione di Padova, Padova, Italy*
[3] *INFN-Sezione di Napoli, Napoli, Italy*
[4] *INFN-Sezione di Milano, Milano, Italy*
[5] *Dipartimento di Fisica, Universit di Napoli "Federico II", Napoli, Italy*
[6] *INFN-Laboratori Nazionali di Legnaro (LNL), Legnaro (PD), Italy*
[7] *CNS - The University of Tokyo, RIKEN campus, Wako, Saitama, Japan*
[8] *Departamento de Fisica Aplicada, Universidad de Huelva, Huelva, Spain*
[9] *INFN-Sezione di Catania, Catania, Italy*
[10] *NIPNE, Magurele, Romania*
[11] *IFJ PAN, Krakow, Poland*
[12] *Dipartimento di Fisica, Universit di Milano, Milano, Italy*
[13] *KEK, Tsukuba, Ibaraki, Japan*
[14] *Department of Physics, Sendai, Miyagi, Japan*
[15] *Institute for Basic Science, Daejeon, Korea*
[16] *China Institute of Atomic Energy, Beijing, China*
[17] *National Centre for Nuclear Research, Otwock, Poland*
[18] *RIKEN Nishina Center, Wako, Saitama, Japan*
[19] *Advanced Science Research Center, JAEA, Tokai, Ibaraki, Japan*
[20] *Department of Physics, University of Ioannina, Ioannina, Greece*
[21] *Heavy Ion Laboratory, University of Warsaw, Warsaw, Poland*
[22] *Department of Physics, University of Athens, Athens, Greece*
[23] *Department of Physics, Kyushu University, Hakozaki, Fukuoka, Japan*
[24] *Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, China*

We investigated the reaction dynamics induced by the Radioactive Ion Beams ^{7}Be and ^{8}B on a ^{208}Pb target at energies around the Coulomb barrier. ^{7}Be is a weakly-bound nucleus (Sα = 1.586 MeV) with a very well pronounced ^{4}He-^{3}He cluster structure and is the loosely bound core of the even more exotic ^{8}B (Sp = 0.1375 MeV) nucleus. The ^{7}Be+^{208}Pb collision was studied at INFN-LNL (Italy), where a 250 kHz secondary ^{7}Be RIB is routinely delivered by the facility EXOTIC [1]. Charged particles originated by the interaction with the target were detected in the laboratory angular ranges [55°,84°], [96°,125°] and [138°,165°] by means of 6 E-Eres telescopes of the newly developed detector array EXPADES [2]. Experimental data were analysed within the framework of the Optical Model by fitting the elastic scattering angular distribution with the code FRESCO [3]. We also measured the differential cross sections for the reaction products ^{3}He and ^{4}He observing that the production yield for the heavier helium isotope is about 5 times larger than for the lighter one. The ^{8}B+^{208}Pb collision was performed with the CRIB-CNS facility at RIKEN (Wako, Japan), with a ^{8}B intensity of 10 kHz and a purity about 25%.

Charged reaction products arising from the interaction with the target were detected by means of six E-Eres modules of the already mentioned detector array EXPADES ensuring the coverage of the following angular ranges in the laboratory frame: [16°,41°], [55°,84°], [96°,125°] and [139°,164°]. The angular distribution for the elastic scattering process were analysed performing an Optical Model best-fit with the code FRESCO. The total reaction cross-sections, extracted for both the investigated collision, were compared together and with the ^{6,7}Li+^{208}Pb collision data [4]. According to the preliminary results, ^{7}Be nucleus reactivity is rather similar to that of its more bound mirror nucleus ^{7}Li whereas the ^{8}B+^{208}Pb total reaction cross section (of about 1 b) appears to be much larger than those measured for reactions induced by the other weakly-bound projectiles on the same target.

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Probing the cluster structure in ^{10}Be using resonant ^{6}He + α scattering

S. Upadhyayula[1], G. Rogachev[1], E. Uberseder[2], B. Roeder[2], A. Saastamoinen[1], J. Hooker[1], H. Jayatissa[2], Y. Koshchiy[1], H. Curtis[1]

[1] *Texas A&M University, Cyclotron Institute*
[2] *Texas A&M University*

There is strong evidence that some states in ^{10}Be exhibit molecular like α:2n:α configuration. Based on theoretical studies it appears that the 6.179 MeV 0^{+} state in ^{10}Be has a pronounced α:2n:α configuration with an α-α inter-distance of 3.55 fm [Itagaki and Okabe, (2000)]. This is 1.8 times more than the corresponding value for the ^{10}Be ground state. The 2^{+} at 7.542 MeV in ^{10}Be is believed to be the next member of this rotational band. The state at 10.2 MeV was identified as a 4^{+} member in recent experiments. The algebraic model predicts that the terminating member of this band is the 6^{+} state that should be found around 13 MeV. We performed an experiment to search for the 6^{+} state in ^{10}Be at around 13 MeV excitation energy in the excitation function for ^{6}He+α scattering. The results of this study will be presented.

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Diagnose Laser-induced Neutrons by Detecting Radiative Capture Gamma-rays

X. XiaoFeng[1]

[1] *China Institute of Atomic Energy*

We used a new experimental scheme to diagnose neutron products in high-intensity laser experiments. By using scintillation detectors, we studied the structures of the time-of-ight signalsrelated to neutrons induced by high-intensity laser. The fast signals which relate to the fast neutron produced in the experiment and the slow signals which relate to the moderated thermal neutrons were recorded at the same time. The results show that delayed gamma-rays resulting from the radiative capture of moderated neutrons can be employed for the neutron diagnosis. The method can partially overcome the detector eciency changes caused by the high-intensity laser radiation, and provide a new way of neutron yield diagnosing in high-intensity laser-target interaction experiments.

Direct measurements and detection techniques with low-energy RIBs

H. Yamaguchi[1]

[1] *Center for Nuclear Study, the University of Tokyo*

Our knowledge for the astrophysical reactions involving unstable nuclei had been limited due to the difficulty of measuring those reactions experimentally. Owing to the recent development of RI beams, some of those reaction rates have been studied newly, or with an improved precision. Direct measurement method of astrophysical reactions is discussed, introducing the thick-target method in inverse kinematics (TTIK). As an example, study on several (α,p) reactions relevant for explosive stellar phenomena are presented. New measurement technique using an active target is also discussed, as an advanced form of thick-target experiment.

The Treiman-Yang Criterion: validating the Trojan Horse Method by experimentally probing the reaction mechanism

S. S. Perrotta[1,2,3], C. Spitaleri[1,2], S. Cherubini[1,2], A. Cvetinović[2], G. D'Agata[1,2], D. Dell'Aquila[4], A. Di Pietro[2], P. Figuera[2], L. Guardo[2], M. Gulino[2,5], I. Indelicato[2], I. Kres[2], M. La Cognata[2], M. La Commara[4,6], L. Lamia[2], D. Lattuada[2,7], M. Lattuada[1,2], I. Lombardo[4,6], M. Mazzocco[8,9], T. Parascandolo[4,6], R. G. Pizzone[2], G. G. Rapisarda[2], S. Romano[1,2], R. Spartà[2], O. Trippella[10,11], A. Tumino[2,5]

[1] *Dipartimento di Fisica e Astronomia, Università degli studi di Catania*
[2] *Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud, Catania*
[3] *Scuola Superiore di Catania*
[4] *Istituto Nazionale di Fisica Nucleare, Sezione di Napoli*
[5] *Facoltà di Ingegneria e Architettura, Università degli Studi di Enna "Kore"*
[6] *Dipartimento di Scienze Fisiche, Università "Federico II", Napoli*
[7] *Extreme Light Infrastructure – Nuclear Physics*
[8] *Dipartimento di Fisica, Università di Padova*
[9] *Istituto Nazionale di Fisica Nucleare, Sezione di Padova*
[10] *Dipartimento di Fisica, Università di Perugia*
[11] *Istituto Nazionale di Fisica Nucleare, Sezione di Perugia*

The dominance of the quasi-free (QF) break-up mechanism in a selected kinematical region of a three-body reaction is a key aspect for the applicability of the Trojan Horse Method (THM) [1, 2]. The Treiman-Yang (TY) Criterion is a model-independent experimental test for the aforesaid mechanism, and hence constitutes one of the strongest validity tests of the THM.

The Criterion was first proposed for high energy particle reactions [3] (where the QF mechanism was initially observed), then extended to non-relativistic three-body nuclear reactions [4]. It exploits the dependencies of the reaction amplitude on the kinematical variables to build a transformation, the "Treiman-Yang rotation", under which the amplitude is expected to be invariant if the quasi-free (QF) break-up is dominant. Passing this test signals that the contribution from other mechanisms with different dependencies is negligible.

In order to verify experimentally the Criterion, it is necessary to measure the reaction cross-section out-of-plane. Such a measurement was carried out back in 1980 for the $^{9}\mathrm{Be}(^{3}\mathrm{He}, \alpha\alpha)\alpha$ reaction [5]. In June 2016, a dedicated experiment was performed at LNS with an improved experimental set-up to apply the test to the $\mathrm{d}(^{10}\mathrm{B}, ^{7}\mathrm{Be}\ \alpha)\mathrm{n}$ reaction, with a $^{10}\mathrm{B}$ beam impinging at 27.5 MeV on a CD_2 target. The analysis of the acquired data is still in progress.

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