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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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The diagnostics of Laser Energy for Nuclear Science Laboratory

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The laser-matter interaction is a subject of considerable theoretical as well as practical importance. The availability of extremely high-power laser beams has opened up new possibilities in the field of research. Laser beams can generate plasma from interaction with solid targets, and, in proper conditions, they can also trigger nuclear reactions. Thus, laser induced phenomena have acquired a great deal of attention from scientists working in a variety of areas like optics, materials science, plasma physics and nuclear fusion.

The future availability of high-intensity laser facilities, capable of delivering tens of petawatts of power into small volumes of matter at high repetition rates, will give the unique opportunity to investigate nuclear reaction under extreme plasma conditions.

Although it is impossible to reproduce the extreme properties of stellar matter, a methodology largely employed in other fields of plasma physics allows to rescale plasma parameters (e.g. temperature and density) in order to make similar to the real world our laboratory conditions. In fact, keV temperature plasmas can be rather easily generated in laboratory, but with densities orders of lower magnitude than the stellar ones [1].

In this contest, at LNS, a new test laboratory - the Laser Energy for Nuclear Sciences laboratory - was realized with the purpose to direct measure the reaction rates of nuclear astrophysics reaction in laser-produced plasmas.

In the LENS laboratory, targets in a vacuum chamber can be fired with a pulse produced by a Q-switched Nd:YAG laser (wavelength of 1064 nm, pulse length of 6 ns, pulse energy up to 2 J) [2]. The beam is focused on a target within a diameter of 100 m, at an angle of $30^{\o}$ with respect to the target normal. The peak intensity is about $2{\cdot}10^{12}$ W/cm^2. To measure the energy of each pulse, the beam passes through an optical sampler that extracts about 1% of the primary beam, which is conveyed onto a pyroelectric energy meter. The primary beam is linearly polarized, and the polarization plane con be rotated by means of a halfwave plate.

Several detectors are used in the vacuum chamber to study the produced plasma. A CCD camera, sensitive to X-ray in the 1-10 KeV range, faces the target. Half of the sensitive surface is used to measure the total X-ray flux, while the other half is covered by a Ti filter in order to operate in a Single Photon regime, allowing to measure the energy spectrum.

An ICCD camera, sensitive to the range 200-900 nm, is placed in front of the target, to image the time-evolution of the plasma plume. It has a fast imaging mode (down to 2 ns exposure), and is used to study the spatial development of plasma over time. Several pick-up and SiC sensors were used as ion collectors and positioned at different distances and angles from the target.

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Characterisation and development of the next generation of VUV low-light sensors for astrophysics applications

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Silicon Photo-Multipliers (SiPMs) have emerged as a compelling photo-sensor solution over the course of the last decade. In contrast to the widely used Photo-Multipliers Tubes (PMTs), SiPMs have high single Photon Detection Efficiency (PDE) with negligible gain fluctuations [1], are low-voltage powered, optimal for operation at cryogenic temperatures, and have low radioactivity levels. Astroparticle physicists benefit from SiPM technology since 2005, when MEPhI-Pulsar SiPMs has been sent in space for cosmic ray studies at the International Space Station. SiPMs are also being considered as a promising photon detector for MAGIC, DARWIN, and GERDA projects [2]. The current generation of Vacuum UltraViolet (VUV) SiPMs achieve at best 25% PDE below 300 nm compared to more than 50% at 420 nm, being limited by reflections and charge carrier collection close to the surface [3]. The aim of this talk is to show a quantitative understanding of the processes that affect SiPM performance. In particular we will show a theoretical framework to describe, for different wavelengths, the SiPM PDE as a function of the bias voltage [4] and the most updated results of SiPMs characterisation at TRIUMF [5]. This project is part of the development of a new generation of VUV SiPMs with a very high efficiency in VUV (>50%), small correlated noise (< 1%) and high Single Photon Timing Resolution (SPTR) for operation in the next generation of astrophysics and large-scale low-background cryogenic experiments such as the next-generation Enriched Xenon Observatory experiment (nEXO).

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Sensitivity Studies of Fusion Reactions in the Crusts of Accreting Neutron Stars

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Observing X-rays from the crusts of neutron stars which are transiently accreting matter onto their surface reveals a lot of information about the nature of dense matter. It also helps explain the structure and composition of neutron star crust. Interpreting this data requires full knowledge of different nuclear reactions which heat or cool the crust leading to patterns in the observed data. Thus, modeling the crust with a comprehensive set of nuclear reactions is of utmost importance. The inputs in these models include masses of the nuclei, fusion reaction rates, electron capture rates, beta-decay half-lives, etc. [1].

The pycnonuclear fusion reaction rates that are used in these models are theoretically calculated by extending phenomenological expressions. As a result, they have high uncertainties spanning several orders of magnitude [2]. We present the first sensitivity studies of these reaction rates by changing them by six orders of magnitude (both enhance and reduce) and characterize their impact on the overall abundance flow. Preliminary results help us identify the most sensitive reactions.

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The apokamp gas discharge phenomenon: experimental and theoretical backgrounds

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In 2016 the group of experimentalists led by Eduard Sosnin (Institute of High Current Electronics, Tomsk, Russia) has been discovered a new phenomenon in low-temperature plasma physics: an extended plasma jet developing perpendicular to the bending point of the pulsed arc discharge channel between two electrodes [1]. This phenomenon occurs if the discharge ignites between two electrodes: first one one is under the high pulse-periodic potential, and the other is having floating potential, i.e. connected via a capacitor to "ground". The discharge has been entitled as "apokamp" (from Greek $\alpha\pi o$ - "off" and $\kappa\alpha\mu\pi\eta$ - "bend"). As it was found, a single needle or a conical jet of 67 cm length being attached to the bending point of the current channel is an apokamp. This unusual new type of gas discharge is observed at high (atmospheric) and medium pressures in gas mixtures usually containing a small portion of electronegative gas, e.g. oxygen or chlorine. It was shown experimentally that apokamp does not exists in highly purificated non-electronegative gases (argon, kripton, nitrogen). It should be noted that depending on voltage pulses parameters, the apokamp can turn into more than one plasma jets in the perpendicular direction to the current channel also [2].

Here we give a first theoretical backgrounds for the apokamp phenomenon in terms of deterministic theory. We use the "two-moment model" [3] of a multicomponent discharge plasma to describe a self-sustained periodic discharge in pure oxygen both in the inter-electrode gap and in the surrounding space above the electrodes. To simplify the consideration of a physical situation the 2D-model is used instead of 3D, so the discharge between two plane electrodes with similar to experimental physical conditions has been considered. In simulations the high-voltage potential is connected to the pulse voltage source through the 10 kOhm ballast load. The floating potential electrode is connected to the ground through the 10 pF capacitance. We also consider a simplified plasma-chemical reactions and species sets for oxygen [4]. Namely, the reduced formulation includes only electrons, neutral molecules O and O_2, positive O_2^+ and negative O_2^- single charged ions. The reactions number are restricted to four most important: electron impact ionization, impact dissociation, electron attachment and ion-ion recombination. We also used non-uniform initial conditions for quasi-neutral plasma density and temperature distribution in the inter-electrode space to perform the simulations in the pre-conditioned medium.

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Study of the ^{22}Ne$(\alpha,\gamma)^{26}$Mg reaction at LUNA

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The ^{22}Ne$(\alpha,\gamma)^{26}$Mg reaction strongly competes with the ^{22}Ne$(\alpha,\mathrm{n})^{25}$Mg reaction which is the main source of neutrons for the s-process in low-mass Asymptotic Giant Branch (AGB) and massive stars. Recently it has been found that the uncertainty of the ^{22}Ne$(\alpha,\gamma)^{26}$Mg reaction rate affects also the nucleosynthesis of isotopes between ^{26}Mg and ^{31}P in intermediate-mass AGB stars. At astrophysical energies, these reaction are characterized by very low cross sections, difficult to measure. The ^{22}Ne$(\alpha,\gamma)^{26}$Mg reaction rate is influenced by the 395 keV resonance which has been studied only indirectly leading to a wide range of possible values for its resonance strength (10^{-15} - 10^{-9} eV).

A direct measurement of the 395 keV resonance of the ^{22}Ne$(\alpha,\gamma)^{26}$Mg reaction is presently ongoing at LUNA (Laboratory for Underground Nuclear Astrophysics), located at Gran Sasso National Laboratory. The rock overburden of about 1400 m (3800 m water equivalent) reduces the muon component of the cosmic background by a factor of 10^6 and the neutron component by a factor of 10^3. A first campaign has been completed, using a windowless gas target filled with 99.99% enriched ^{22}Ne gas at 1 mbar and the α beam provided by the 400 keV accelerator. An high efficiency BGO detector has been used. From this first campaign only an upper limit for the 395 keV resonance strength has been estimated.

In order to improve the results of the first campaign, a new campaign of the ^{22}Ne$(\alpha,\gamma)^{26}$Mg reaction is currently ongoing at LUNA. A new borated polyethylene shielding has been implemented to reduce the neutron contamination due to the environmental background.

Effect of compound nuclear reaction mechanism in ^{12}C(^{6}Li,d)reaction at sub-Coulomb energy

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The determination of the Asymptotic Normalization constant(ANC) of the two ^{16}O states viz. 6.92 MeV (2^{+}) and 7.12 MeV (1^{-}) are of utmost importance in the determination of the ^{12}C(α,γ) cross-section at 300 keV [1].This capture reaction determines the ratio of the ^{12}C to the ^{16}O abundance at the end of helium burning in stars. The direct measurement of the alpha capture reaction cross-section at 300 keV is almost impossible and hence an extrapolation by R-matrix method is required to obtain the desired cross-section at Gamow energy. The ANC constrains R-matrix extrapolation of the ^{12}C(α,γ) astrophysical S-factor from the fit of the measured direct data at energies above E_{cm} = 1 MeV. The determination of the ANC can be done from the alpha transfer reactions ^{12}C(^{6}Li,d) and ^{12}C(^{7}Li,t) by a comparison of the measurement with a suitable direct reaction model. Here the angular distribution of the ^{12}C(^{6}Li,d) reaction populating the 6.92 and 7.12 MeV states of ^{16}O at sub-Coulomb energy (E_{cm} = 3 MeV) are analysed in the framework of the Distorted Wave Born Approximation (DWBA). Recent results on excitation function measurements and backward angle angular distributions derive ANC for both the states on the basis of an alpha transfer mechanism. In the present work [2], we show that considering both forward and backward angle data in the analysis, the 7.12 MeV state at sub-Coulomb energy is populated from Compound nuclear process rather than transfer process but the 6.92 MeV state is however produced from direct reaction mechanism.

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Multidiagnostics setups for Magnetoplasmas devoted to Astrophysics and Nuclear Astrophysics Research in Compact Traps

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Magnetized plasmas in compact traps may become experimental environments for the investigation of nuclear beta-decays of astrophysical interest. In the framework of the project PANDORA (Plasmas for Astrophysics, Nuclear Decays Observation and Radiation for Archaeometry) the research activities are devoted to demonstrate the feasibility of an experiment aiming at measuring lifetimes of radionuclides of astrophysical interest when changing the charge state distribution of the in-plasma ions and the other plasma parameters such as density and temperature. This contribution describes the multidiagnostics setup now available at INFN-LNS, which allows unprecedented investigations of magnetoplasmas properties in terms of density, temperature and CSD. The setup includes an interfero-polarimeter for total plasma density measurement, a multi-X-ray detectors system for X-ray spectroscopy (including time resolved spectroscopy), an X-ray pin-hole camera for high-resolution 2D space resolved spectroscopy, a two-pin plasma-chamber immersed antenna for the detection of plasma radio-self-emission, and different spectrometers for the plasma-emitted visible light characterization. The setup is also suitable for other studies of astrophysical interest, such as turbulent plasma regimes dominated by the so-called Cyclotron Maser Instability, which is a typical kinetic turbulence occurring in astrophysical objects like magnetized stars, brown dwarfs, etc. A description of recent results about plasma parameters characterization in quiescent and turbulent Electron Cyclotron Resonance-heated plasmas will be given.

Study of the neutron induced reaction $^{17}O(n,\alpha)^{14}C$ at astrophysical energies via the Trojan Horse Method

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Neutron induced reactions play a fundamental role in the nucleosynthesis of elements in the universe. Indeed, to correctly study the reactions involved in the well-known s-process in stars, which produce about half of the elements beyond the iron peak, it is mandatory to know the neutron abundance available in those stars. The $^{17}O(n,\alpha)^{14}C$ reaction is one of the so-called "neutron poisons" for the process and it could play an important role in the balance of the neutron abundance. The reaction is therefore investigated in the energy range of astrophysical interest by applying the Trojan Horse Method to the three body reaction $^{2}H(^{17}O,\alpha^{14}C)H$. In this talk the experiment will be discussed, showing also the preliminary results of the data analysis.

New Astrophysical factor and reaction rate of ^{12}C(α,γ)^{16}O

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^{12}C(α,γ)^{16}O capture reaction is considered to be the most important thermonuclear reaction in non-explosive astrophysical sites and its reaction rate is an important nuclear parameter in many stellar evolution models. This reaction was investigated through the direct α-transfer reaction (7Li, t) at 28 and 34 MeV incident energies [1]. After the determination of the reduced α-widths of the subthreshold 2^{12} and 1^{12} states of ^{16}O from the DWBA analysis, we determine the E2 and E1 S-factor at the radius r=6.5 fm and 7.7 fm from 0.01MeV to 4.2MeV in the center-of-mass energy. With numerical integration, we will determine at the radius r=6.5 fm the new reaction rate of ^{12}C(α,γ)^{16}O at a different stellar temperature (0.06 GK-2 GK) and particularly at Gamow peak energy (0.2 GK).

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How do charged environments affect low-energy fusion rates? Screening effects in laser-induced non-neutral plasmas

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The cross-section of nuclear fusion reactions induced by charged particles at ultra-low energies (few keV) depends exponentially on the collision energy, as the process is dominated by the tunneling through the Coulomb barrier. Consequently, even relatively small energy differences may induce sensible variations in the yields. In this presentation, the fusion rate modifications provoked by a positively charged environment are discussed, from the theoretical point of view, for inertial confinement fusion [1] and cluster Coulomb explosion [2] plasmas, both important in the field of terrestrial nuclear fusion energy production.

The problem was approached via the screening potential approach [3], deriving approximate analytical results by evaluating the average screening potential for some scenarios of interest. The developed model predicts [4] that fusion is hindered for reactions between thermal fuel nuclei, while an enhancement is expected for secondary and "beam-target" reactions. Depending on the plasma conditions, the modifications can be relevant even for relatively small net charges in the environment (several % difference or more in the fusion rate for an average net charge per nucleus of 10^{-5} proton charges).

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Preliminary results for the ^{19}F(p,α)^{16}O reaction cross section measured at INFN-LNS

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The production and destruction of fluorine is strictly connected to the physical conditions in stars. Its cosmic origin is still uncertain and widely debated. Because of this, fluorine abundances will place a severe constraint on stellar evolution models. The ^{19}F(p,α)^{16}O reaction is an important fluorine destruction channel in the proton-rich outer layers of asymptotic giant branch (AGB) stars [1] and it might also play a role in hydrogen-deficient post-AGB star nucleosynthesis [2]. At present time, theoretical models overproduce F abundances in AGB stars with respect to the observed values [3], thus calling for further investigation of the nuclear reaction rates involved in the production and destruction of fluorine. In the last years, new direct and indirect measurements improved significantly the knowledge of ^{19}F(p,α)^{16}O cross section at deeply sub-Coulomb energies (below 0.8 MeV) [4]. Unfortunately, those data are larger by a factor of 1.4 with respect the previous data reported in the NACRE compilation in the energy region 0.6-0.8 MeV [5].

Using the Large High Resolution Array of Silicons for Astrophysics (LHASA), we performed a new direct measurement of the ^{19}F(p,α)^{16}O. The goal of this experiment is to reduce the uncertainties in the nuclear reaction rate of the ^{19}F(p,α)^{16}O reaction. Experimental details, calibration procedure, angular distributions and some preliminary results will be presented.

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Study of $^{14}N(p,\gamma)^{15}O$ resonance reaction at E_{lab}=278keV

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The bottleneck of the CNO cycle is ^{14}N(p,γ)^{15}O reaction (Q value = 7297 keV), which plays an important role in the stellar energy production. The level width of a sub - threshold resonance state of ^{15}O at E_x=6792 keV ($E_{c.m.}$= - 504 keV) is crucial. However its width has not been determined unambiguously so far [1].

The ^{14}N(p,γ)^{15}O resonance state at 7556 keV ($E_{c.m.}$= 259 keV & total width $\approx$ 1 keV) was populated in an experiment at Tata Institute of Fundamental Research, Mumbai using low energy proton beam from an ECR (Electron Cyclotron Resonance) based accelerator [2]. An implanted ^{14}N target [3] on Ta backing was used (energy thickness ΔE $\approx$ 21 keV). The target was carefully characterized using several techniques [4]. RBS (Rutherford backscattering spectrometry) measurements were performed to determine the stoichiometry of the implanted target. The ion implantation profile was simulated with TRIM [5] and SUSPRE ion implantation calculator [6]. Unlike TRIM, experimental depth profile nicely matched with the SUSPRE calculation considering the target as bare Ta. So, N_2 atoms took the interstitial positions rather than the substitutional positions of the substrate atom (Ta). The proton beam energy was varied from 276 keV to 312 keV in steps of 2 - 3 keV. Two HPGe detectors with 18% and 30% relative efficiency were used for the measurements. They were placed at seven different angles ranging from 0^o to 137^o. Both the detectors were placed at 5 cm from the target position. Relative efficiency data were collected with standard radioactive sources. Appropriate Monte Carlo simulations were also done to take care of the changes during the in-beam experiment.

In the gamma decay channel, the 7556 keV state de-excites to populate the 5181 keV, 6172 keV and 6792 keV states of ^{15}O. The lifetimes of those states were measured using Doppler Shift Attenuation Method (DSAM). The centroid shifts of the gamma rays at different positions of the detector were clearly seen in the experimental spectrum. To evaluate the centroid shift value properly, the calibration of the detectors was made with proper care. The lifetime of the 6792 keV state was obtained with less uncertainty than the previous reported values [1]. Resonance strength ($\omega\gamma$) was determined from the stoichiometry of the implanted target and the maximum yield at the plateau region of the yield curve. Large basis shell model calculations also have been performed using NuShellX code [7] to obtain the spectroscopic factors of the resonance state as well as the low lying states in ^{15}O. The calculated spectroscopic factors are in good agreement with experimental values in most of the cases.

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Elastic Scattering of ^{8}Li on heavy and medium mass targets with SOLEROO capability at ANU

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Exotic nuclei such as ^{8}Li and ^{6}He have weakly bound neutrons around a relatively tightly bound core, which have a strong influence on nuclear reaction mechanisms, especially at bombarding energies near the Coulomb barrier [1][2]. The weak intensity of these radioactive beams makes precision measurements challenging and we do not yet understand the influence of weak-binding and breakup on fusion.

To achieve a better understanding of the reaction dynamics of these nuclei, the SOLEROO (Solenoidal Exotic Rare Isotope Separator) radioactive ion beam (RIB) capability has been developed at the Australian National University (ANU). This capability is based on a 6.5 T superconducting solenoidal separator which produces RIBs by in-flight transfer reaction via interactions with a primary target [3]. Following production, all the reaction products enter the solenoid and the desired RIBs are separated using a 6.5 T axial magnetic field and focussed on to a secondary target. The secondary beam is tracked with two parallel plate avalanche counters (PPACs) [4] placed immediately after the solenoid. Beam purities of about 98% can be achieved by rejecting unwanted beam species using this tracking facility. Surrounding the secondary target, high efficiency double sided silicon strip detectors are placed in a wide angular range to measure reaction products.

One key quantity to understand is the interaction potential for these exotic nuclides with various targets. To define the interaction potential, elastic scattering angular distributions for ^{8}Li on ^{208}Pb, ^{209}Bi and ^{58}Ni at energies near and above the barrier have been measured. The secondary beam of ^{8}Li incident on the secondary target has a finite divergence and a finite beam spot size. Using the information from the PPAC tracking detectors, the true scattering angle has been reconstructed on an event-by-event basis which allows measurement of reliable elastic scattering angular distributions [5]. To normalise this elastic scattering distribution to Rutherford scattering, the beam spot and divergence in the experiment are fed in to a Monte Carlo simulation which essentially takes in to account the axial asymmetry of the beam profile. Detailed optical model calculations have then been performed to extract reaction cross-sections for the above systems. Considering the complexity of measuring elastic scattering angular distribution, the reaction cross-sections have also been extracted using the Sum-of-Differences method [6] and have been compared. The obtained reaction cross-sections at above barrier energies have then been compared with the measured reaction cross-sections for ^{6}Li, ^{7}Li, ^{9}Li and ^{11}Li.

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Bound state beta-decay of $^{205}Tl^{81+}$ ions

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Beta decay of highly charged ions has attracted much attention in recent years. An obvious motivation for this research is that stellar nucleosynthesis proceeds at high temperatures where the involved atoms are highly ionized. Another important reason is addressing decays of well-defined quantum-mechanical systems, such as one-electron ions where all interactions with other electrons are excluded. The largest modifications of nuclear half-lives with respect to neutral atoms have been observed in beta decay of highly charged ions. These studies can be performed solely at ion storage rings and ion traps, because there high atomic charge states can be preserved for extended periods of time (up to several hours).

In the case of bound state beta-decay [1], the emitted electron occupies one of the vacant atomic orbitals accompanied by the emission of a quasi monochromatic antineutrino. The measurement of the bound state beta-decay rate of fully-ionized ^{205}Tl ions is needed to determine the matrix element for the electron capture decay of the 2.3 keV excited state in ^{205}Pb to the ground state of ^{205}Tl. This matrix element is important for the determination of pp-solar neutrino capture probability into the 2.3 keV state of ^{205}Pb.

In this talk, the preparation for the bound state beta-decay experiment for the case of fully stripped $^{205}Tl^{81+}$ ions [2] will be discussed. I will also discuss some simulation results done for the experiment to be performed next year at GSI, Darmstadt.

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Study of $^3He(n,p)^3H$ reaction at cosmological energies with Trojan Horse Method.

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One of the cornerstones of the Big Bang cosmological model is the Big Bang nucleosynthesis (BBN). A series of 12 reactions converts the initial protons and neutrons into helium isotopes and a very small, although very important amount of ^7Li. In this network of reactions, the $^3He(n,p)^3H$ has an important role which impacts the final ^7Li abundance. The Trojan Horse Method (THM) has been applied to the $^3He(d,pt)H$ reaction in order to extract the astrophysical $S(E)$-factor in the Gamow energy range. The experiment was performed thanks to Notre Dame Tandem of the Physics and Astronomy Department of the N.D. University (USA). In this poster the experimental setup will be described together with the first preliminary result.

Transfer reactions as an Indirect Method in Nuclear Astrophysics

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The use of indirect methods in nuclear astrophysics is prompted by the known difficulties that one encounters in attempting to make direct nuclear astrophysics measurements. Mainly, the fact that in stars, many reaction partners are unstable nuclei, some with very short lifetimes, and the fact that reactions in stars occur at very small energies (10s-100s keV) and the corresponding cross sections are very small and as such, difficult to measure.

In my presentation, I will discuss the use of transfer reactions as an indirect method of determining information important for nuclear astrophysics. Specifically, I will focus on peripheral reactions and their analysis with the Asymptotic Normalization Coefficients (ANC) method. I will present results from related experiments that have been conducted at Cyclotron Institute, Texas A&M University with focus on the Optical Model Parameters (OMP) obtained and the need of reliable calculations.

Additionally, I will describe the improvements in the measured data that we obtained after upgrading the detection system used and how this affects the OMP determination.

Astrophysical S-factor for the ^{2}H(p,γ)^{3}He reaction at big-bang nucleosynthesis energies

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The ^{2}H(p,γ)^{3}He radiative capture has a major role in big-bang nucleosynthesis (BBN). The uncertainty in this reaction rate has a strong impact on primordial abundances of ^{2}H, ^{3}He and ^{7}Li. In order to determine the reaction rate and its associated uncertainty, one requires the astrophysical S-factor, which is deduced either from the measured data or a nuclear reaction model. The latest BBN calculation of Coc *et al.* [1] predicts the primordial deuterium to hydrogen ratio of ^{2}H/H = $(2.45\pm0.10)\times10^{-5}$. This result is in good agreement with that of Cooke *et al.* [2], ^{2}H/H = $(2.527\pm0.030)\times10^{-5}$, deduced from astrophysical observations. However, as now the observed deuterium abundance is known at the percent level, the same precision is expected on the theoretically predicted result. Hence, there is an urge for accurately measured nuclear cross section (S-factor) of the ^{2}H(p,γ)^{3}He reaction in the BBN energy range of interest. The total cross section for this reaction has already been measured in the past by several research groups. The LUNA Collaboration [3] obtained a considerable amount of data for a very low energy region (up to E = 22 keV). However, there are only a few data points reported for the 30-300 keV energy range [4-7], relevant for BBN, and they seem to be in a disagreement with the recent *ab-initio* calculation of Marcucci *et al.* [8]. The most recent measurements, reported by Ma *et al.* [4], unveil a discrepancy in the S-factor of $\approx$ 20% with respect to the values obtained by calculation of Ref. [8]. This disagreement leads to further complications, since one cannot reliably estimate the energy dependence of the S-factor, which is crucial to determine the reaction rate and primordial abundances.

We expected that the study of the angular distribution of the ^{2}H(p,γ)^{3}He reaction in the BBN energy range might be a key factor to get the existing experiments in agreement with the present theory, since the calculation of Marcucci et al. [8] exhibits a strong angular dependence of the differential cross section, while the previous experimental studies assumed an almost isotropic angular distribution of this reaction. We performed an extensive study of the ^{2}H(p,γ)^{3}He reaction by measuring its cross section and γ-ray angular distribution in the BBN energy range. In the first stage of the experiment, the absolute differential cross section was measured at 135°with respect to the incident beam direction, using E_{p} = 260 keV proton beam incident on two deuterated titanium targets. In the second stage, the γ-ray angular distribution was determined using two HPGe detectors placed at 90°and 135°with respect to the proton beam. The angular distribution of the ^{2}H(p,γ)^{3}He reaction turned out to be anisotropic and very well described by the calculation of Marcucci et al. [8]. In addition, the theoretically predicted S-factors [10] are in reasonable agreement with our experimental findings. Therefore, we suggest that the present theory [8] can be used in BBN calculations.

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DETERMINATION OF THE ASYMPTOTIC NORMALIZATION COEFFICIENT (NUCLEAR VERTEX CONSTANT)FOR $\alpha + d \to {}^6$Li FROM THE NEW DIRECT MEASURED $d(\alpha, \gamma)^6$Li DATA AND ITS IMPLICATION FOR EXTRAPOLATING THE $d(\alpha, \gamma)^6$Li ASTROPHYSICAL S FACTOR AT EXTREMELY LOW ENERGIES

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In the present work, the results of the analysis of the experimental astrophysical S factors (AS) $S_{exp}(E)$ [1,2] for the nuclear-astrophysical $d(\alpha, \gamma)^6$Li reaction directly measured at extremely low energies E are presented. One notes that the $d(\alpha, \gamma)^6$Li reaction is of great interest as one of the sources of the ^6Li creation in the early Universe [1].

The analysis is performed within the modified two-body potential method [3]. The method involves two additional conditions that verify the peripheral character of the direct radiative capture reaction $d(\alpha, \gamma)^6$Li: 1) $R(E, b) = const$ for arbitrary variation of the free model parameter b for each fixed experimental value of the energy E; 2)The ratio $C^2_{d\,\alpha} = \frac{S^{exp}(E)}{R(E;b)}$ must not depend neither from b and nor from the energy E for each experimental point of the energy $E = E_i \quad (i = 1, 2 \ldots)$ where $R(E; b) = \frac{S^{(sp)}(E;b)}{b^2}$ in which $S^{(sp)}(E; b)$ is a single-particle astrophysical S factor (SPAS) and b is the amplitude of the tail of the radial s-component wave function of the bound $^6Li(= \alpha + d)$ state.The latter is calculated in the framework of the shell model with the phenomenological Woods-Saxon potential containing the geometric parameters (the radius r_0 and the diffuseness a).The value of b strongly changes as a function (r_0, a)-pair, i.e., $b = b(r_0, a)$. Fulfillment of the conditions above, firstly, it makes it possible to remove the model dependence of the calculated direct $S(E)$ on the geometric parameters r_0, and a both for the two-body bound $(\alpha + d)$ state and the(αd)-scattering one being within the experimental errors.Secondly, it allows to determine experimental value of $C^2_{d\,\alpha} = (C^{exp}_{d\,\alpha})^2$ and its uncertainty by model-independent way. The obtained $(C^{exp}_{d\,\alpha})^2$ values can be implemented in the expression $S(E) = (C^{exp}_{d\,\alpha})^2 R(E, b)$ for obtaining the extrapolated values of $S(E)$ and its uncertainties within the energy range $E < E_1$, including $E = 0$.

Variation of values of the parameters r_0, and a is done in the wide range ($1.13 \le r_0 \le 1.37fm$, $0.58 \le a \le 0.72fm$, $2.37 \le b \le 2.86fm^{-1/2}$) and is shown that the reaction is strongly peripheral.As a result, the ANC $(C^{exp}_{d\,\alpha})^2$ and $S(70keV)$ values were obtained. They are equal to $(C^{exp}_{d\,\alpha})^2 = 5.41 \pm 0.18(exp)\pm 0.12$(theor) fm^{-1} and $S(0) = 2.425 \pm 0.081$ $(exp) \pm 0.034$(theor) MeVnb. The obtained results are compared with those from other authors.

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The isolation time of the Solar System

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Remapping what happened shortly before the formation of the Solar System (SS) is a challenging task. However, we can uncover the possible reasons for its early composition. The abundance of some radioactive nuclei at the formation of the SS are well-measured based on primeval meteoritic samples. Using a galactic chemical evolution code, we compare the predicted abundance of several radioactive nuclei to their measured early SS values. Most of them were less abundant than calculated - the apparent deficit can be explained by the physical isolation of the matter of the SS from the galactic interstellar medium 20-100 million years before the Sun formed. The results from different nuclei show that the value of the isolation time correlates with their parent nucleosynthesis process, which means that different events may stopped contributing to the composition of the SS earlier than others. However, ^{26}Al (with half-life 0.7 Myr) is more abundant in the early SS than what the model predicts, which is evidence for a nearby event soon before the formation of SS. These results may be suitable to have an insight to the prehistoric times of the SS as well as to test the validity of the current models for the production of radioactive nuclei in stars.

Can Inhomogeneous Primordial Magnetic Field Affect Nucleosynthesis in the Early Universe?

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In the standard big bang nucleosynthesis (BBN) model, there is a long-standing cosmic Lithium Problem that predicted primordial ^{7}Li abundance is 4 times higher than the observation.

The effect of primordial magnetic field (PMF) on BBN has been studied in the case that a constant scale-invariant PMF strength during the BBN epoch was assumed, which virtually did not solve the Lithium Problem [1]. Theoretically, the length scale of the PMF fluctuations inside the co-moving horizon scale in its energy density can survive during the BBN epoch. It is therefore realistic to assume that the PMF was in the inhomogeneous distribution which satisfies extrapolated observational constraints from CMB anisotropies. We have recently studied the effects from such inhomogeneous PMF on the BBN [2]: The primordial baryons are in local equilibrium with the same temperature and obey Maxwellian distribution; Globally, due to the existence of a fluctuated PMF, radiation energy density becomes inhomogeneous as the radiation temperature does.

In this talk, we will extensively show our recent new results so that the inhomogeneous PMF eventually leads to a non-Maxwellian baryonic energy distribution function and eventually affects strongly the primordial ^{7}Li abundance. Moreover, we find that our extended multi-zone BBN calculation results in the same effect as the BBN model with an inhomogeneous PMF would make [3]. In this extended calculation, the multi-zone inhomogeneous PMF is encoded into nuclear reaction network code. This code can be used in the future studies of BBN under the various circumstances that the cosmological plasma evolution could make including fluctuations and magneto-hydrodynamical processes in the early Universe.

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