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Measurement of the ^{140}Ce(n,γ) cross section at n_TOF

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(The n_TOF Collaboration)

Abstract
Among the nucleosynthesis mechanism involving the heavy nuclei, the so-called slow (s-)process is one of the better known. Being responsible of about half of the element heavier than iron, many models were built in order to describe the process and the final element abundances.
The s-process take place in the outer layer of the AGB stars, where the heavy elements are produced through a succession of neutron captures and beta decays. The accurate knowledge of the neutron capture cross sections for all the elements involved in the process plays a key role, therefore in last decades great efforts have been undertaken in order to improve the accuracy of these data.

At the n_TOF facility at CERN a recent experiment to measure the ^{140}Ce neutron capture cross section has been performed, motivated by a large discrepancy between the models predictions and the astronomical observation for the cerium abundance[1]. This measurement was characterized by an unprecedented combination of the high energy resolution of the n_TOF neutron beam and a highly enriched ^{140}Ce sample. The experimental apparatus was based on four gamma detectors based on C_6D_6 liquid scintillators, which are characterized by a very low neutron sensitivity.

In total, 81 resonances were measured and fitted. For each, the capture and neutron widths were determined, highlighting the large discrepancies respect to the major nuclear libraries. These new data allowed to calculate the ^{140}Ce(n,g) MACS with an uncertainty lower than 5%, significantly improving the experimental data available for the libraries update.

Study for the long-lived gamma background due to neutron emitting calibration reactions

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Abstract
In this article, a detailed study has been done on the long-lived gamma background due to neutron emitting reactions. It mainly focused on the experiments that will be used to calibrate energy with the terminal voltage of an upcoming Facility for Research in Experimental Nuclear Astrophysics (FRENA). FRENA is a high current low energy (0.2-3) MV tandetron accelerator primarily dedicated to experiments related to nuclear astrophysics with very low cross-sections (~pb to nb). It is located at Saha Institute of Nuclear Physics, Kolkata, INDIA. This machine can deliver a proton beam with an energy range between 400 keV to 6 MeV with beam intensity >μ300 A. Many reactions like (p,n), (p,γ) have been utilized in various accelerator facilities around the globe for energy calibration purposes. Neutron emitting reactions like ^{7}Li(p,n), ^{13}C(p,n), ^{19}F(p,n), ^{27}Al(p,n), etc. have been very commonly used. A significant number of neutrons produced from such experiments can interact with surrounding elements like copper, tantalum, stainless steel (SS304 and SS316), concrete materials, etc. These interactions may cause long-lived gamma activity in the vicinity of the accelerator. Background gammas from these radioactive isotopes can interfere with gamma measurements in future experiments. The present study has been done to investigate those possibilities of gamma background which may occur due to the calibration study by neutron emitting experiments. Here ^{7}Li(p,n), ^{13}C(p,n), ^{19}F(p,n) and ^{27}Al(p,n) reactions having neutron threshold energies 1.8803, 3.2355, 4.2351, 5.8036 MeV respectively are chosen keeping in mind the proton energy available at the facility.

Throughout the ACTAR TPC performances for Nuclear Physics measurements

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Abstract

The study of the nucleon interactions and a better understanding of the nuclear structure is essential in different nuclear physics fields. The measurements of the most relevant quantities for such studies is a real challenge sometimes. Exotic nuclei are often used to observe rare processes and decays.

All these new challenges require devices to be more and more performant and precise.

One of the rising systems recently developed is the ACtive TARget Time Projection Chamber (ACTAR TPC). Based on the time projection chamber principle, the purpose of such a detector is to perform an efficient tracking of the ions, with high precision evaluation of the particle energy loss along the tracks for their identification.

In this work we'll report on the ACTAR TPC placed at GANIL laboratory (Grand Accélérateur National d'Ions Lourds), in Caen, France. The preparation for the next experimental campaign and a characterization of this complex instrument for proton scattering measurements with heavy ions is reported.

Cross section measurements of low-energy charged particle induced reactions using moderated neutron counter arrays

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Abstract
Experimental investigations of low-energy charged particle induced reactions with applications in nuclear astrophysics and nuclear reactor physics are performed using ^{3}He moderated neutron counter arrays at the 3 MV and 9 MV Tandem accelerators of the Horia Hulubei – National Institute for Physics and Nuclear Engineering in Romania. We present the first neutron production cross sections and average neutron energy measurements with proton beams on ^{nat}Cu and ^{27}Al targets. The ^{nat}Cu(p,xn) well known reaction was studied in the 4.5 MeV to 14 MeV proton energy range and used for the calibration of the detector array. Afterword, the ^{27}Al(p,n)^{27}Si reaction was investigated in the astrophysically relevant energy range of 5.8 MeV to 6.75 MeV. The measurements were performed with a 5 keV step that allows the study of the resonant structures of the reaction cross section. An updated neutron configuration array will be further used for studies with α beams of the thermonuclear reaction

$^{27}Al(\alpha,n)^{30}P$ (Q= – 2.642 MeV), which has an astrophysical interest in connection with nucleosynthesis in the solar system and in stars during explosive burning.
The new experimental results for the $^{nat}Cu(p,xn)$ and $^{27}Al(p,n)$ measurements will be compared with preceding data. The $^{nat}Cu(p,xn)$ reactions cross sections and average energies of the neutron emission spectra are compared to statistical model calculations.

Experimental study of $^{37}Cl(\alpha,n)^{40}K$ reaction in order to constrain the reaction rate of destruction of ^{40}K in stars

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Abstract

Nuclei in the intermediate-mass region are of great interest for nuclear astrophysics [1], yet the experimental data in that mass region are deficient. The unstable isotope ^{40}K is one of the main isotopes responsible for the radiogenic heating of the mantle in an Earth-like exoplanet. In addition, small quantities of the isotope may be present in the earth's core. The radiogenic heat keeps the mantle and the outer core (which mainly consists of molten iron and nickel) in a state of turbulent convection. The heat-induced motion of the core generates the earth's magnetic field, which is essential for developing a habitable environment [2]. In addition, the heating of the mantle controls the formation of plate tectonics, the development of the volcanic activity, and the recycling of carbon on a planet. The abundance of ^{40}K in a planet depends on the composition of the interstellar medium from which it formed. Thus, nuclear reactions that determine the amount of $^{4}0K$ during stellar evolution are not only crucial for understanding the fundamental mechanisms of potassium nucleosynthesis but may also play an essential role in understanding the habitability potential of earth-like exoplanets.

In this study, we aim to constrain the $^{40}K(n,\alpha)^{37}Cl$ reaction rate, one of the two major destruction paths of ^{40}K in stellar nucleosynthesis by measuring the reverse reaction $^{37}Cl(\alpha,n)^{40}K$ and applying the principle of detailed balance as we have done before for the $^{40}K(^{40}K(n,p)^{40}Ar$ reaction rate) [3]. In a first measurement we performed differential cross-section measurements on the $^{37}Cl(\alpha,n_1\gamma)^{40}K$, $^{37}Cl(\alpha,n_2\gamma)^{40}K$ and $^{37}Cl(\alpha,n_3\gamma)^{40}K$ reaction channels, for six different center of mass energies in the range between 5.1 and 5.4 MeV. The experiment took place at the Edwards Accelerator

Laboratory of Ohio University. The gamma rays from the reaction channels mentioned above were detected by two LaBr3 scintillators. Using the swinger facility to change the angle of the beam on target with respect to the detection system, we were able to take measurements for the differential cross-section at six different angles between 20° and 120° in the lab system. In this presentation, we present some preliminary results of this ongoing analysis.

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Study of (α,n) reactions to determine the α-optical potential for γ-process

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Abstract

The neutron capture process produces nuclei heavier than iron in the stars. But 30-35 proton-rich heavy nuclei from ^{74}Se-^{196}Hg (known as p-nuclei) are formed by the γ-process, instead of neutron capture. γ-process is a combination of (γ,α), (γ,n), and (γ,p) reactions on heavy nuclei at high γ-flux scenario. The α-optical potential is one of the primary input parameters for calculating the reaction rate of (γ,α)-process using the Hauser-Feshbach(HF) statistical model and principle of detailed balance. The optical potential is calculated from elastic scattering angular distribution data at high energies. As a result, a modification in potential is required for low- energy astrophysical reactions. An alternative approach for improving the α-optical potential at low energy was proposed, based on the (α,n) reaction, which is solely dependent on the α-transmission coefficient, i.e. on the alpha optical potential. In this work, an energy-dependent α-optical potential form was obtained by fitting the (α,n) reaction cross-section data of p-nuclei in the mass range A = 92-168. The new potential is a modified McFadden-Satchler (McF) potential with depth parameters (both real and imaginary) changed by an energy dependent Fermi function. This α-optical potential is used to calculate (α,γ) reaction cross-section using the HF model and compared to the existing experimental results.

Experimental studies of the ^{46}Mn beta-decay channel and spectroscopy of ^{46}Cr at LISE-GANIL

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Abstract

Stars with initial mass greater than 8 $M_\odot$ end their lives through a Core Collapse Supernova (CCSN) explosion. Besides, ^{44}Ti nucleosynthesis takes place in CCSN; making this nucleus a good gamma astronomy tracer for Super Nova (SN) events due to the characteristic gamma rays emitted on its decay chain. Furthermore, the comparison between observations and models of the synthetized ^{44}Ti in CCSN gives important constrains to the models. In the later, reaction networks are used for modelling nucleosynthesis occurring in the last stages of those stars with thermonuclear reaction rates as its inputs [1,2,3].

Unfortunately, a direct measurement of the cross section for a given thermonuclear reaction is extremely difficult in the current laboratories worldwide. Therefore, indirect methods can be used for this purpose, especially when the reaction rate is dominated by a narrow isolated resonance. In this context, beta-delayed proton emission is very useful with (p,γ) reactions involving low and medium mass proton-rich radioactive nuclei. That is a consequence of the fact that in those reactions narrow isolated resonances are likely to occur [1,4].

In this work we present the preliminary results of analyzing the ^{46}Mn decay channel as a way to study the ^{45}V(p,γ)^{46}Cr reaction. This is due to the thought that nucleosynthesis of ^{44}Ti in CCSN explosions is quite sensitive to that reaction [5]. The 46Mn was selected among other species in the cocktail beam delivered by LISE fragment separator at GANIL (Caen, France) in order to study its beta decay and the excited states of his daughter nucleus ^{46}Cr. We present the proton and gamma emission peaks related to the ^{46}Mn decay and compare them with the work from references [6,7].

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Towards the measurement of live ^{182}Hf from deep-sea ferromanganese crusts by accelerator mass spectrometry

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Abstract
The vast majority of naturally-occurring isotopes with a mass greater than iron are produced by neutron capture. Depending on the actual neutron flux during nucleosynthesis, half of the isotopes are by-products of steady stellar fusion (s-process). The other half are thought to be produced in abrupt and high neutron flux events via rapid uptake at the neutron dripline (r-process). Possible scenarios include certain types of supernovae of massive stars or neutron-star mergers [1]. Abundance patterns of r-process nuclides in combination with the radioactive decay of long-lived isotopes can be used to constrain the production site. Recent results of ^{60}Fe ($T_{1/2}$ = 2.6 Myr) and ^{244}Pu ($T_{1/2}$ = 81.3 Myr) measured from Pacific Ocean crusts led to the conclusion that r-process yields of recent supernovae in the vicinity of our solar system were not sufficient to explain the abundance of r-process nuclides in our Galaxy [2].
Measuring the abundance of the long-lived radioisotope ^{182}Hf ($T_{1/2}$ = 8.9 Myr) together with ^{60}Fe and ^{244}Pu from terrestrial archives could propel the decade-long search to pin down r-process nucleosynthesis events in the vicinity of our solar system that produced the heaviest elements [3].
Accelerator mass spectrometry (AMS) is the method of choice to directly measure minute traces of radioisotopes with suppression of molecular and atomic isobars. In addition, at the Vienna Environmental Research Accelerator (VERA) facility, we developed an ion-laser interaction mass spectrometry (ILIAMS) setup to filter challenging medium-mass isobaric background [4]. It uses a radio frequency quadrupole ion guide filled with a reactive buffer gas (i.e., He and O_2 mixtures), where an intense laser is collinearly overlapped with the ion beam. This instrument exploits differences in the electron detachment energy or molecular reactions of negatively charged, thermalized ions. While less-strongly bound unwanted species

(i.e. $^{182}WF_5^-$) are efficiently removed from the ion beam, the wanted species ($^{182}HfF_5^-$) remain unaffected and are injected into the subsequent AMS system. [3]. Currently, the suppression of $^{182}WF_5^-$ background relative to $^{182}HfF_5^-$ of > 10^5 is only achieved by reactions using He+O_2 (30:1) buffer gas. Our recently 170-fold improvement compared to previous work set the current limit of detection of ^{182}Hf/Hf to about $6x10^{-14}$ on commercial HfF4 [3].
In order to improve the detection efficiency and to further increase isobar suppression, a new design of the ILIAMS ion guide is planned to accommodate large emittance ion beams, blown up from intense F^- ion currents, and suitable for a UV laser to efficiently neutralize WF_5^-. In addition, in-situ beam diagnostics shall provide information on dissociation and detachment reactions inside ILIAMS. To reliably validate any improved detection limits on the order of ^{182}Hf/Hf = 10^{-14}, a dilution series of material of known ^{182}Hf/Hf ratio in that range is needed.

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Direct measurement of $^{26}Si(\alpha, p)^{29}P$ reaction for the nucleosynthesis in the X-ray bursts at CRIB

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Abstract

Nuclear reactions in the αp-process are important for the nucleosynthesis in X-ray bursts. However, there are not sufficient experimental data of the reactions because radioactive-isotope beam is required to perform the experiment. The $^{26}Si(\alpha,p)^{29}P$ reaction is one of the most important reactions in the X-ray burst, and direct measurement of this reaction was performed at CNS RI beam separator (CRIB), located at RIKEN Nishina Center. We used inverse kinematics with a thick target for the measurements. In this experiment, multiplexer circuits called MUX were used to acquire data from many channels. The details of the experimental condition and the results of the analysis to date are discussed.

Investigating the predicted breathing-mode excitation of the Hoyle state

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Abstract

Knowledge of the low-lying monopole strength in ^{12}C—the enigmatic Hoyle state in particular—is crucial for our understanding of both the astrophysically important triple-α reaction and of α-particle clustering in general. Multiple theoretical models have predicted a breathing mode of the Hoyle State at $E_x \approx 9$ MeV, corresponding to a radial in-phase oscillation of the underlying α clusters. The ^{12}C(α,α')^{12}C and ^{14}C(p,t)^{12}C reactions were employed to populate states in ^{12}C in order to search for this predicted breathing mode. A self-consistent, simultaneous analysis of the inclusive spectra, together with angular distributions of charged-particle decay,

yielded clear evidence for excess monopole strength at $E_x \approx 9$ MeV which is highly collective. Reproduction of the experimentally observed inclusive yields using a fit, with consistent population ratios for the various broad states, required an additional source of monopole strength. The interpretation of this additional monopole resonance as the breathing-mode excitation of the Hoyle state may support D_{3h} symmetry for the Hoyle state itself. However, some recent calculations also support different interpretations for both the Hoyle state and the additional monopole strength. Independent of the detailed structure, this excess monopole strength may complicate the analysis of the properties of the Hoyle state, modifying the temperature dependence of the 3α rate at $T_9 \approx 2$ and ultimately, the predicted nucleosynthesis in explosive stars.

Direct measurement of the $^{19}F(p,\alpha)^{16}O$ reaction

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Abstract

The $^{19}F(p,\alpha)^{16}O$ reaction is important for understanding the fluorine abundance in the outer layers of asymptotic giant branch (AGB) stars and it might also play a role in hydrogen-deficient post-AGB star nucleosynthesis. Up to now, theoretical models overproduce F abundances in AGB stars with respect to the observed values, thus calling for further investigation of the reactions involving fluorine. Indeed, in the last years, new direct and indirect measurements improved significantly the knowledge of the $^{19}F(p,\alpha_0)^{16}O$ cross section at deeply sub-Coulomb energies (below 0.8 MeV).
Nevertheless, those data are larger by a factor of about 1.4 with respect to the previous data reported in the NACRE compilation in the energy region 0.6-0.8 MeV. In order to solve these discrepancies, we present here a direct experiment performed at INFN-LNS using a silicon strip detector array (LHASA - Large High-resolution Array of Silicon for Astrophysics). Our results clearly confirm the trend of the latest experimental data in the energy region of interest. The $^{19}F(p,\alpha)^{16}O$ reaction rate is the sum over the (p,α_0), (p,α_π) and the (p,α_γ) channels. While the (p,α_0) rate is well constrained by the present existing data, down to the lowest energies, almost nothing is known from experiments on the (p,α_π) and (p,α_γ) rates. Despite its importance, the S-factors and the branching ratio between the α_0, α_π and α_γ outgoing channels in the $^{19}F(p,\alpha)^{16}O$ reaction are still largely uncertain at astrophysical energies, emphasizing the need for better measurements. Thus, a direct measurement using the new detector, ELISSA (Extreme Light Infrastructure – Silicon Strip Array), coupled with LHASA will be performed in September 2022 at IFIN-HH. Thanks to the good

resolution of the setup, there will be a good identification of the outgoing channels, thus allowing us to discriminate the (p,α_π) and (p,α_γ) reaction rates at very low energies.

Nuclear level densities and γ−ray strength functions of ^{120,124}Sn and their application in astrophysics

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Abstract

The concepts of the nuclear level density (NLD) and γ−ray strength function (GSF) are two essential tools for the statistical description of excited nuclei and their γ−decay, used in numerous large-scale astrophysical calculations of abundances of elements in the universe [1]. One of the widely used experimental techniques, the Oslo method [2] was applied to the ^{120,124}Sn isotopes to extract these statistical quantities to be further exploited as a nuclear input for astrophysical purposes.

Firstly, the experimental GSFs were used to address the question on the validity of the generalised Brink-Axel hypothesis (gBA) [3, 4], adopted as a crucial assumption in the Oslo method and astrophysical calculations of neutron capture cross-sections within the statistical model formulated by Hauser and Feshbach [5].

In its most general form, the hypothesis states an independence of the GSF of properties of initial and final excited states and dependence on the γ energy only. To ensure the reliability of the slopes and absolute values of extracted strengths, the Oslo method results were cross-checked with the strengths obtained with the novel Shape method [6] and with the relativistic Coulomb excitation experiment [7]. Comparison of all strengths for both nuclei demonstrates a good agreement within the estimated error bars below the neutron separation energy. Moreover, this agreement suggests that the gBA hypothesis holds for the studied cases in this energy region and can be considered valid for any astrophysical calculations.

Finally, the experimental GSFs and NLDs of ^{120,124}Sn were further used as an input to the nuclear reaction code TALYS to calculate the Maxwellian-averaged cross section for the ^{119}Sn(n,γ)^{120}Sn and ^{123}Sn(n,γ)^{124}Sn reactions. These results will be presented for the first time; they are expected to provide better constrains of the neutron capture cross-sections for these nuclei than the theoretical GSF and NLD models included in the TALYS code. As both nuclei demonstrate quite significant resonance features below the neutron separation energy, such as the pygmy dipole resonance, this study also allows to address the particular importance of this nuclear feature for rates of the astrophysical s and r processes in the vicinity of Sn isotopes in the nuclear chart.

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^{7}Li(n,γ)^{8}Li Cross Sections Using ToF Tagged Neutrons

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Abstract

^{7}Li(n,γ)^{8}Li reaction is highly important in the case of stellar nucleosynthesis, where the ^{6}Li, ^{7}Li yields are utilized for studying the evaluation state of star. There the ^{7}Li(n,γ)^{8}Li will act as the Li destruction reaction through β^{-} followed by α emission from ^{8}Li. Due to the lesser cross section, this reaction is not well explored especially in the 3^{+} resonance region. The ^{7}Li(n,γ)^{8}Li reaction cross sections in the neutron energy range of 10 keV to 1 MeV are measured using time of flight tagged neutrons from Am-Be source. The time of flight is generated between the the 4.4 MeV prompt γ in ^{9}Be(α,n)^{12}C reaction and the prompt γs from ^{8}Li in ^{7}Li(n,γ) reaction. The non-resonant and 3^{+} resonant contribution of the excitation function have been identified in this measurement.

The measured cross sections were reproduced with Direct Capture model calculations, including FRESCO-CRC analysis.

Overview of Numerical Simulations for Calculating In-Plasma β-Decay Rates in the Framework of PANDORA Project

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Abstract

Immersing radioactive nuclei in environments composed of energetic charged particles like stellar plasmas can result in β-decay rates orders of magnitude different from those measured terrestrially. Accurate knowledge of the relation between plasma parameters and nuclear decay rates is essential for reducing uncertainties in present nucleosynthesis models. Currently, the full effect of a charge state distribution (CSD) as exists in plasmas is only modelled theoretically but PANDORA (**P**lasmas for **A**strophysics, **N**uclear **D**ecay **O**bservations and **R**adiation for **A**rchaeometry) aims to be the first experiment to verify these models by measuring β-decay rates of select isotopes diffused in electron cyclotron resonance (ECR) plasmas. The experimental methodology is built around tagging and counting the secondary γ-photons emitted during the decay, thus reconstructing the isotope half-life. An endeavor of this magnitude hoping to convert a traditionally observational science into an experimental field naturally requires an extensive study into the properties of the medium, to isolate the photons of interest from the self-emission background as well as to deconvolve the measured spectrum into its space-resolved components. In terms of ECR plasmas, this translates to careful analysis of the interplay between RF power and frequency, gas pressure, type of ion and chamber geometry which strongly influence the microscopic variation in plasma properties. We present here an overview of an optimized 3D particle-in-cell (PIC) code suite aimed at modelling electron and ion dynamics in a self-consistent manner, capturing the most relevant physics for each and capable of furnishing space-resolved information on density, energy, CSD and atomic level populations. A comparison of simulation results with their experimental counterpart is also presented for benchmarking the tools. Additionally, we also discuss the inputs required by the model of Takahashi and Yokoi for calculating the perturbed decay rates and how they are correlated with the outputs from the PIC code suites. We conclude with some

perspectives on ongoing upgrades to the models and the potential to use them for both fundamental and applied research involving ECR ion sources.

Cross section of proton capture reactions on Se and Mo isotopes relevant to the astrophysical p-process

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Abstract

Low energy proton capture cross sections on heavy isotopes are necessary for a better understanding of the astrophysical p-process. There are around 35 proton-rich stable isotopes between ^{74}Se and ^{196}Hg which are bypassed by the s- and r- process are commonly referred as p-nuclei [1, 2] whose origin is still not completely understood. In the present study, proton capture reactions are studied on Se and Mo isotopes at astrophysically relevant energies using nuclear modular code TALYS [3]. The isomeric ratios and partial cross sections are also obtained for ^{92}Mo and ^{78,80}Se cases. The obtained results are compared with the literature data taken from EXFOR [4] data library. We have also calculated astrophysical S-factor and reaction rates inside a core-collapse supernova. In addition, the effect of different combinations of the nuclear input parameters entering the stellar reaction rate have been investigated.

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Laboratory magnetoplasmas as experimental environment for β-decay investigations of astrophysical interest

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Abstract

Theoretical models predict considerable variations in the β-decay properties in highly ionized nuclides, which would have a strong impact on stellar nucleosynthesis processes. The PANDORA collaboration has recently conceived a new experimental approach aimed at using laboratory magnetized plasmas (capable of emulating some stellar conditions) as an environment for in-plasma β-decays investigations. In the fully superconducting high performance PANDORA trap, a hot plasma containing a known concentration of β-decaying atoms can be confined and kept in dynamic equilibrium for weeks. The decay rate can be measured by detecting the γ-rays emitted by the daughter nuclei (through an array of 14 HPGe detectors) and correlated as a function of the average ionization state of radioactive ions using synergically an advanced plasma multi-diagnostic system. PANDORA represents a promising experimental setup to verify, for the first time, the theoretical predictions on the dependance of lifetime on temperature, to investigate the expectations deriving from nucleosynthesis calculations and to extract information on plasma emissivity and opacity in specific range of plasma temperature and density of crucial interest for benchmarking astrophysical observations from kilonovae. This contribution describes the theoretical background, the experimental approach and preliminary results of a fully virtual experimental run which includes PIC plasma simulations, fluid-dynamics of isotopes injection in plasma and GEANT4 simulations modelling the response of the HPGe array. The sensitivity of the PANDORA setup was checked by estimating the duration of the experimental run to obtain sufficient statistical significance in terms of σ-confidence levels. The analysis was specifically carried out for the first three physical cases of the phase-1 (^{176}Lu, ^{134}Cs, ^{94}Nb) involved in crucial branching points in s-processing nucleosynthesis, and selected according on the scientific relevance and expected effects on the lifetime due to ion CSD or temperature.

The $^{12}C + ^{16}O$ fusion reaction in carbon burning: study at energies of astrophysical interest using the Trojan Horse Method

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Abstract

Carbon burning is a fundamental process for the advanced stages of a massive star ($M>8M_{\odot}$) evolution. It mainly occurs through the $^{12}C+^{12}C$ fusion, however at temperatures higher than 10^9 K the $^{12}C+^{16}O$ fusion can become prevalent due to the increased abundance of ^{16}O in the ashes of the helium burning. The $^{12}C+^{16}O$ reaction also plays a role both in the explosive carbon burning and in the oxygen burning. Thus, the astrophysical energy region of interest ranges from 3 to 7.2 MeV in the center-of-mass frame. In the literature there are various measurements of the cross section between 4 and 7.2 MeV in the center-of-mass, however, none of them goes below 4 MeV, making extrapolation necessary. Recently the reactions $^{16}O(^{12}C,\alpha)^{24}Mg$ and $^{16}O(^{12}C,p)^{27}Al$ have been studied in the entire energy region of astrophysical interest by applying the Trojan Horse Method to three-body processes $^{16}O(^{14}N,\alpha^{24}Mg)^{2}H$ and $^{16}O(^{14}N, p^{27}Al)^{2}H$. In this talk, after a brief description of the method, the experimental setup as well as the preliminary phases of the data analysis will be presented and discussed.

Reassessment of the gamma-decay branch of the Hoyle State

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Abstract

The triple-alpha process is one of the most fundamental processes in stellar nucleosynthesis, and in particular, the stellar production of carbon. ^{12}C is created through this triple-alpha process where a superposition of three helium nuclei can access the Hoyle State in ^{12}C. Most of the time this superposition will decay back into three alpha-particles, with a very low probability of creating stable ^{12}C.

The creation of stable carbon happens mainly through two available decay branches. This is either a gamma cascade or pair production, leaving the ^{12}C in its ground state. The radiative width of the gamma-branch has been measured several times between the period 1961 to 1976 [1,2,3,4,5,6,7]. Most of the measurements performed up until 1976 have yielded results which are in good agreement with one another. However, a recent measurement performed in 2019 by Kibédi et al. [8] yielded a significantly larger radiative branching ratio (Γ_{rad}/Γ) which disagrees with all previous measurements.

Given the astrophysical significance of the Hoyle state, resolving this conflict is crucial. Therefore, new measurements have been performed to reinvestigate the gamma-decay branching ratio of the Hoyle state. The experiment has been performed at the Oslo Cyclotron Laboratory through the $^{12}C(p,p'\gamma\gamma)$-reaction. In the experiment the scintillation array OSCAR was used, consisting of 30 $LaBr_3(Ce)$-detectors, together with our silicon particle telescope SiRi [9]. Using this combination has resulted in a dataset with much higher statistics than ever for this measurement. Results from this measurement will be presented, together with the analysis method and experimental details.

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Sub-Coulomb barrier penetration for a 6Li with a clustered and deformed ground-state

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Abstract

The dynamics of barrier penetration, which is often modelled neglecting the reactants internal structure, plays a primary role in nuclear reactions taking place at collision energies of astrophysical interest. The process can also be relevant with regards to the "electron screening problem" [1], the excess of enhancement observed in the cross-section of several nuclear reactions of astrophysical interest, measured in fixed-target experiments, with respect to the expected effect of the electrons in the projectile and target.

In this work, we study the penetrability of the Coulomb barrier of ^{6}Li from the theoretical point of view, focusing on the role of clustering and deformations in the nucleus ground-state. Specifically, we will consider the case of ^{6}Li – p scattering.

Improving on the semi-classical model in ref. [1], we consider a quantum two-cluster structure to describe the 6Li nucleus, based on a d – α interaction including a tensor component [2]. From such structure we deduce a tensorial ground-state form factor (similarly to the construction in ref. [3]) to be adopted in the ^{6}Li–p barrier penetrability calculation. We study the effect of the quadrupole deformation in the ^{6}Li wave-function on the result. The computed penetrability is compared with that associated with available optical potentials for the projectile-target interaction, and with experimental data. Possible future improvements of the model are briefly discussed.

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The challenging direct measurement of the 65 keV resonance strength in $^{17}O(p,\gamma)^{18}F$ at LUNA

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Abstract

The $^{17}O(p,\gamma)^{18}F$ reaction plays a crucial role in AGB nucleosynthesis as well as in explosive hydrogen burning occurring in type Ia novae. At the temperatures of interest for the former scenario (20 MK < T < 80 MK) the main contribution to the astrophysical reaction rate comes from the poorly constrained E_R = 65 keV resonance. The strength of this resonance is presently determined only through indirect measurements, with an adopted value $\omega\gamma = (1.6 \pm 0.3)$ 10^{-11} eV [1].

A new high sensitivity setup has been installed at LUNA, located at Laboratori Nazionali del Gran Sasso [2]. The underground location of LUNA 400kV guarantees a reduction of the cosmic ray background by several orders of magnitude. The residual background was further reduced by a devoted shielding. On the other hand the 4π-BGO detector efficiency was optimized installing an Al target chamber and holder. With more than 300 C accumulated on Ta_2O_5 targets, with nominal ^{17}O enrichment of 90%, the LUNA collaboration has performed the first ever direct measurement of the 65 keV resonance strength [3].

In the talk the setup details and preliminary results of the challenging direct measurement performed at LUNA will be reported.

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On the impact of compact binary ejecta opacity on kilonova transient signals

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Abstract

Returns of gravitational wave astronomy will largely benefit from the detection and identification of electromagnetic (EM) signatures to gravitational-wave sources. Kilonovae (KN) are promising EM counterparts to compact binary mergers, offering to astronomers and nuclear astrophysicists a unique window to advance knowledge on the heavy-element nucleosynthesis and merger-driven mass ejection. However, extremely heterogeneous post-merging ejecta composition of both light and heavy-r process nuclei, implies strong effects on the KN light-curve identification due to the varying opacity of the system. Hence, large uncertainties on the r-process nucleosynthesis final abundance from the spectroscopic analysis of the KN signal are still present, hardly fixed by theoretical models. Here we will present some peculiar features of the KN studies, focusing on the opacity issue, from the atomic and plasma physics perspectives. In this view, recent efforts have been made trying to constrain on plasma opacity of interest for early-stage KN emission, and we will discuss some of the experimental progresses on the problem, including instruments and methods which open to an interdisciplinary approach to tackle astrophysical problems in laboratory plasmas.

Indirect measurement of the $^{126}Sb(n,\gamma)^{127}Sb$ cross section from experimental level density and γ-strength function

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Abstract

Nuclei in the ^{135}I region have been identified as a possible bottleneck for the i process. Nuclear properties such as the Maxwellian-averaged cross section are indispensable tools when trying to explain nucleosynthetic processes, but the instability of the region prevents us from carrying out direct measurements. In order to investigate it, we propose an indirect approach.

At the Oslo Cyclotron Laboratory we carried out the $^{124}Sn(\alpha,p\gamma)^{127}Sb$ reaction in order to extract the nuclear level density and the γ ray strength function of ^{127}Sb using the Oslo method, with the aim of calculating the Maxwellian-averaged cross section and the neutron-capture rate of the A-1 nucleus ^{126}Sb.

The level density in the low excitation-energy region agrees well with known discrete levels, and the higher excitation-energy region follows an exponential curve compatible with the constant temperature model. The strength function between $E_\gamma \approx 1.5$-8.0 MeV presents several features, such as an upbend and a possibly double-peaked pygmy-like structure. None of the theoretical models included in the nuclear reaction code TALYS seem to reproduce well the experimental data.

The Maxwellian-averaged cross section for the $^{126}Sb(n,\gamma)^{127}Sb$ reaction has been experimentally constrained by using our level-density and strength-function data as input to TALYS. The results show good agreement with the JINA REACLIB, TENDL and BRUSLIB libraries, while the ENDF/B-VIII.0 library predicts a significantly larger cross section.

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$^{13}C(\alpha,n)^{16}O$: The Potential Source of Neutrons for the s-Process

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Abstract

The sources of neutrons represent a longstanding and debated open problem among the key process for stellar nucleosynthesis [1]. Neutron-captures process were early recognized as the most important mechanism to produce the elements heavier than iron. Various reactions have been identified as promising neutron sources. Among them $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$ represent the most favoured candidates. The $^{13}C(\alpha,n)^{16}O$ reaction operates in the He-burning shell of low-mass ($M<4M_{\odot}$) AGB stars [2] and it is the neutron source reaction that allows the creation of the bulk of the s-process elements such as Sr, Zr and the light rare earth elements in the universe. In order to understand $^{13}C(\alpha,n)^{16}O$ reaction mechanism, the cross-section of this s-process neutron source reaction is required to study in the energy range of astrophysical interest. In this context, excitation function of $^{13}C(\alpha,n)^{16}O$ reaction has been calculated using nuclear model based calculations [3,4]. We have also calculated reaction rates and astrophysical factor S(E) for $^{13}C(\alpha,n)^{16}O$ reaction in stellar environment and compared it with available literature data [5,6].

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Direct measurement of the low energy resonances in $^{22}Ne(\alpha,\gamma)^{26}Mg$ reaction

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Abstract

$^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$ are considered the two important neutron sources for the s- process, but there is still uncertainty about the total available neutron flux for the s-process. $^{13}C(\alpha,n)^{16}O$ determines the neutron production in AGB stars while $^{22}Ne(\alpha,n)^{25}Mg$, which occurs during core helium and carbon shell burning, acts as the primary neutron source in massive stars. But the $^{22}Ne(\alpha,n)^{25}Mg$ reaction has a negative Q-value = -478 $\pm$ 0.05 keV and hence operates only at high temperatures, e.g., the peak of helium burning, and during C-shell burning (if sufficient ^{22}Ne is available). Moreover, the neutron-producing role of $^{22}Ne(\alpha,n)^{25}Mg$ is complicated by the competing $^{22}Ne(\alpha,\gamma)^{26}Mg$ reaction, which has a positive Q-value = 10614.74 $\pm$ 0.03 keV and therefore starts operating at relatively lower temperatures, before $^{22}Ne(\alpha,n)^{25}Mg$ can kick in. Hence it is important to investigate the reaction rate of $^{22}Ne(\alpha,\gamma)^{26}Mg$ in order to put quantitative constraints on the neutron production for the weak s-process. It was experimentally observed by the direct measurements that the reaction rate for $^{22}Ne(\alpha,\gamma)^{26}Mg$ is strongly impacted by the low energy resonance at E_α(lab) = 828 keV, but the recent indirect measurements show that the resonance at E_α(lab) = 653 keV can appreciably impact the $^{22}Ne(\alpha,\gamma)^{26}Mg$ reaction rate. The measurement of both these resonances was performed at Sanford Underground Research facility (SURF), CASPAR. Preliminary analysis of the resonance strengths for these two resonances will be presented.

Study of proton captures on carbon isotopes at LUNA

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Abstract
Both the $^{12}C(p,g)$ and 13C(p,g) reactions are the key for understanding the mixing processes inside AGB stars. The carbon isotopic ratio can be readily derived from stellar spectra, thus constraining the reaction rates in a wide temperature range can give more insight for the mixing models. Nevertheless, cross section measurements at energies close to the Gamow window are challenging due to the exponential drop in the cross sections of charged particle reactions.
For this reason, the data reported in literature are affected by significant statistical and systematic uncertainties.

In a recent experiment at the Laboratory for Underground Nuclear Astrophysics (LUNA), both reactions have been studied using two types of solid targets. Furthermore, different detection techniques - HPGe spectroscopy, total absorption spectroscopy and activation counting – were employed in order to obtain several independent datasets. This approach addressed the necessity of both limiting systematic uncertainties and monitoring the targets under the intense (~400 uA) beam of the LUNA 400 kV accelerator. We present the experimental techniques employed with some innovative analysis methods, and the preliminary results obtained in the c.m. energy range of 65-360 keV.

Relativistic quantum theory and ab initio simulations of electroweak decay spectra in nuclei of astrophysical interest.

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Abstract

In this presentation we focus first on the theoretical methods and relevant computational approaches to calculate the electronic and nuclear structures within the mean-field approximation of the Dirac equation for many-particle systems. The self-consistent numerical solutions are obtained by using either radial mesh or Gaussian basis sets. Furthermore, we describe the extension of our relativistic approach to deal with nuclear reactions driven by the weak force, such as the electron capture and β-decay, also at finite temperature in astrophysical scenarios, using the Fermi-Dirac statistics. The latter processes are indeed major drivers of the nucleo-synthesis of the elements in stars and, thus, their understanding is crucial to model the chemical evolution of the Universe. In particular, we analyze the Zr(93) ---->Nb(93), the Lu(176) ---->Hf(176) and the Kr(85) ---->Rb(85) β- decays.

(p,n) reaction measurements in inverse kinematics with SECAR.

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Abstract

Neutron-induced reactions are essential to nucleosynthesis of the elements heavier than iron. Recent studies show that key (n,p) reactions, such as the ^{56}Ni(n,p)^{56}Co and ^{64}Ge(n,p)^{64}Ga, regulate the efficiency of the so-called neutrino-p process (νp-process), which contributes to the production of elements between nickel (Ni) and tin (Sn) in type II supernovae. Nucleosynthesis in νp-process occurs at regions of slightly proton-rich nuclei in the neutrino driven wind of core-collapse supernovae, via a sequence of proton-capture reactions and (n,p) reactions. The small abundance of neutrons needed originates from anti-neutrino captures on free protons.

The recoil mass separator, SECAR (SEparator for CApture Reactions) at FRIB, has been initially designed with the required sensitivity to study (p,γ) and (a,γ) reactions, directly at astrophysical energies in inverse kinematics, with heavy ion and radioactive beams. However, the study of (n,p) reactions via the measurement of the reverse (p,n) reactions in inverse kinematics is also feasible at SECAR. While such proton-induced reaction measurements are particularly challenging, as the recoils and the unreacted projectiles have nearly identical momenta, an appropriate separation level can be achieved with SECAR. Therefore, along with the in-coincidence detection of neutrons these measurements become attainable. The preparation of the SECAR system for accommodating its first (p,n) reaction measurement, including the development of alternative ion beam optics, and the setup of the in-coincidence

neutron detection, along with preliminary results from the p(^{58}Fe,n)^{58}Co reaction measurement, are included in this presentation.

Accelerator Mass Spectrometry of ^{134}Cs & ^{135}Cs for nuclear astrophysics

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Abstract

^{134}Cs is an important branching point in the s-process which defines the ^{134}Ba/^{136}Ba ratio in meteorites. ^{134}Ba and ^{136}Ba are both pure s-process nuclides, as they are shielded from the r-process by the stable/long-lived ^{134}Xe and ^{136}Xe. For this branching point two nuclear parameters are important [1]:

- The beta-decay rate of ^{134}Cs at stellar temperatures
- The ^{134}Cs(n,γ)^{135}Cs cross sections at keV energies

The neutron capture cross section of the ^{134}Cs(n,γ)^{135}Cs reaction at astrophysical neutron energies has not yet been measured. Patronis et al. calculated the cross sections for neutron energies ranging from 5 keV to 100 keV to be on the order of 1 barn [2]. The direct measurement of this cross section is extremely challenging: One needs to handle high radioactivities with a ^{134}Cs target and ^{135}Cs is radiometrically not measurable in the presence of ^{134}Cs, as it is a pure beta emitter with a low end-point energy and a rather long but not very well-known half-life between 1.3 and 3 Myrs. Therefore, mass spectrometric methods need to be developed, which suffer from stable barium and molecular interferences in the used materials.
At the Accelerator Mass Spectrometry (AMS) facility VERA of the University of Vienna, we developed a measurement procedure to measure the isotopic ratio of cesium isotopes by Ion-Laser Interaction Mass Spectrometry (ILIAMS). There, we exploit differences in the electron detachment energies of CsF_2 and BaF_2 by overlapping the low-energy anion beam with a laser beam of suitable photon energy. The energy of the photons has to be higher than the detachment energy of the interfering isobar (BaF_2^-) and lower than that of the isotope of interest (CsF_2^-). The photons neutralize

the BaF_2^- anions by laser-photodetachment ($BaF_2^- + \gamma \rightarrow BaF_2 + e^-$), while leaving CsF_2^- nearly unaffected. To maximize the interaction time between the laser beam and the ion beam, the ions are decelerated and cooled in a He buffer gas filled radiofrequency quadrupole, before they are reaccelerated and injected into the AMS system.

With this method, we are currently able to measure isotopic ratios down to $^{135}Cs/^{133}Cs = 1\times10^{-11}$, with isobaric suppression factors of > 10^8 of the whole AMS system. By irradiating <mg amounts of stable Cs with keV neutrons, isotopic ratios in the range of $^{135}Cs/^{133}Cs \approx 10^{-14}$ and $^{135}Cs/^{134}Cs \approx 10^{-7}$ are achievable in realistic irradiation times. AMS has the potential of reaching these isotopic ratios with the ILIAMS method, but we still suffer from problems mainly in the ion source concerning negative ion output and cross contamination from one sample to another. In this talk, I will present a status report of first achievements and an outlook of ^{135}Cs measurements at VERA.

References

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