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Extending radiative transfer simulations in kilonovae towards non-equilibrium regimes

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The recent observations of several neutron-star merger events and associated electromagnetic transients, particularly AT2017gfo observation, provided robust indications that heavy r-process elements such as lanthanides and eventually actinides can be synthesised in these explosive environments [1]. Nonetheless, pinpointing particular features in the spectra, and linking them to the absorption and emission lines of distinct elements has presented a significant challenge [2,3,4].

One critical obstacle in the analysis is a severe lack of atomic data required to model the expansion's late epochs (> 4 days after the NSM). While it is reasonable to assume that the matter is in local thermodynamic equilibrium (LTE) and that atomic absorption processes dominate in the early hours (< 1 day after the NSM), LTE cannot be assumed for nebular epochs (non-LTE). During these late stages, significant processes include photoionization, ionisation and excitation by electronic impact, and electronic recombination, for which data is scarce.

In this work, we focus on performing large-scale atomic calculations on selected key elements, which are likely to have identifiable features in the spectra of the kilonova AT 2017gfo. Our approach, is therefore aimed at extending existing radiative transfer simulations to non-local thermodynamic equilibrium (NLTE) conditions. We try to overcome the limitations of current models, which often rely on approximations, leading to significant discrepancies in predicting spectral features. As highlighted by recent studies, conventional approaches, such as the Axelrod Van Regemorter treatments, can under- or overestimate effective collision strengths by orders of magnitude [5], impacting the accuracy of the simulated spectra and the intensity of line features.

The core of the calculations were done using the Flexible Atomic Code (FAC) [6] employing a configuration interaction approach, and a central potential that is optimised iteratively, making use of machine learning methods to better reproduce existing experimental data [7]. As to benchmark our calculations, we also use the general non-relativistic AUTOSTRUCTURE code, which has been extensively used and tested for opacity calculations in supernovae.[8]

References

[1] Abbott, B. P. et al. (2017). Gravitational Waves and Gamma-Rays from a BinaryNeutron Star Merger: GW170817 and GRB 170817A. *Astrophys. J.* 848(2) L13. https://doi.org/10.3847/2041-8213/aa920c

[2] Domoto, N. et al. (2022). Lanthanide Features in the Near-infrared Spectra of Kilonovae. Astrophys. J. 939(1)8. https://doi.org/10.3847/1538-4357/ac8c36

[3] Gillanders, J. H. et al. (2023). Modelling the spectra of the kilonova AT2017gfo –II: Beyond the photospheric epochs. Mon. Not. Astron. Soc. (accepted). https://doi.org/10.1093/mnras/stad3688

[4] Vieira, N. et al. (2024). Spectroscopic r-process Abundance Retrieval for Kilonovae. II. Lanthanides in the Inferred Abundance Patterns of Multicomponent Ejecta from the GW170817 Kilonova. Astrophys. J. 962(1) 33). https://doi.org/10.3847/1538-4357/ad1193

[5] Pognan, Q. et al. (2021). On the validity of steady-state for nebular phase kilonovae. *Mon. Not. Astron. Soc.* 510(3) 3806–3837. https://doi.org/10.1093/mnras/stab3674

[6] Gu, M. F. et al., The flexible atomic code, *Can. J. Phys.*, vol. 86, no. 5, pp. 675–689, 2008. https://doi.org/10.1139/P07-197

[7] Flörs, A. et al., Opacities of singly and doubly ionized neodymium and uranium for kilonova emission modeling, Mon. Not. Astron. Soc. vol. 524, no. 2, pp. 3083–3101, 2023. OUP. https://doi.org/10.1093/mnras/stad20

[8] Badnell, N. R., AUTOSTRUCTURE: General program for calculation of atomic and ionic properties, 2016.

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Systematic optical potentials for cluster-structured nuclei reactions

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Within the IANNA framework, we propose new instruments for nuclear reactions measurements, systematical data and theoretical analyses. In Seville (Spain), we have the National Accelerator Centre (CNA), where a permanent experimental setup is coupled to the 3MV tandem accelerator. Such a setup is based on MARS (Modular Apparatus for nuclear Reactions Spectrometry). With MARS, first exploratory measurements are being performed to the 6Li+12C system. Within the IANNA collaboration, experimental campaigns on 12,13C+119,120Sn (2023) and 12,13C+64Zn (2024) were recently carried out in the LAFN (São Paulo, Brazil). Data analyses are ongoing.
With these data, we propose to study the optical potential (OP) strengths, and their energy dependence, in reactions involving stable, tightly and weakly bound, and exotic nuclei projectiles on different targets, at energies around the respective Coulomb barriers.
Moreover, we analyze experimental elastic scattering angular distributions of 4,6He, 6,7Li, 9,10,11Be and 8B impinging on 64Zn and 120Sn targets. Within the data set, we report on optical model (OM) calculations and the determined OP, with the respective uncertainties quantification, based on the double-folding (DF) São Paulo potential (SPP). Within the SPP approach, the best-fit parameters, from OP study, correlate with projectile breakup process, at scattering energies around the Coulomb barrier. Thus, we propose optimum energies for which the projectile breakup shows to be favored, as a function of the projectile breakup Q-value and the Coulomb barrier of the system. The results show to be systematical, when analysing different weakly bound nuclei projectiles impinging on targets with different masses (and atomic numbers). The OP and their capability of predicting optimum projectile breakup yields, as a function of energy, represents important tools for other applications such as planning new experiments on weakly bound nuclei reactions or extrapolating it to Astrophysical systems/energies.

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Iberoamerican Collaboration on Weakly Bound Nuclei: Brazil, Argentina and Spain

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Nuclei generally exhibit cluster structures. Light, stable, or exotic nuclei such as ^{6,8}He; ^{6,7,8,9,10,11}Li; ^{7,8,9,10,11}Be; ^{12,13,14}C are combinations of neutrons, isotopes of hydrogen (^{1,2,3}H), and/or helium (^{3,4}He). Their reaction dynamics depend on their binding energies, as evidenced by experimental observations of breakup or transfer reactions. Consequently, describing the reactions of both exotic and stable nuclei with the same theoretical approach is one of the greatest challenges in Nuclear Physics.

To address this challenge, an international program focusing on weakly bound stable nuclei reactions, such as ^{6,7}Li, ^{9,10}Be, ^{10,11}B, and ^{12,13}C, has been initiated. The primary objective is to investigate nuclear reactions within the gap between helium and carbon, where abundances of Li, Be, and B are notably low, and nuclei with mass numbers A=5 and A=8 are unstable. Furthermore, the synthesis of heavy nuclei from light elements necessitates overcoming the instability gap at mass numbers A=5 and A=8.

This international collaboration brought together researchers from the Open Laboratory of Nuclear Physics at the Institute of Physics of the University of São Paulo (LAFN-IFUSP) in Brazil, the National Commission of Atomic Energy (CNEA) in Argentina, and the Atomic, Molecular and Nuclear Physics department of the University of Seville in Spain. An overview of the results obtained through this collaboration, along with insights from the new experimental setup and preliminary results, will be presented.

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How can inclusive Coulomb break-up measurements help in determining astrophysical radiative capture reaction rates?

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A direct link between the Coulomb inclusive break-up probability and the radiative capture reaction rate for weakly bound systems can be established [1]. This link provides an indirect method to estimate reaction rates of astrophysical interest. This procedure can also assess the validity of different theoretical approaches that have been used to calculate reaction rates. In particular, this procedure is useful for systems in which the relevant reaction cross section cannot be measured directly, or it is experimentally unfeasible at present, such as three-body reactions [2] or short-lived initial nuclei [3].
Results will be presented for the three-body radiative capture reaction rates ^{4}He$(2n,\gamma)^6$He and ^{9}Li$(2n,\gamma)^{11}$Li, for which inclusive break-up experimental data exist [4-6] and theoretical three-body models are developed [6,7]. For ^{6}He case, the available experimental data provide a reaction rate that is considerably larger than the theoretical estimation. For that reason, a new experiment has been carried out recently at TRISOL facility (NSL, University of Notre Dame) for the reaction of ^{6}He$+^{208}$Pb at an energy around the Coulomb barrier (approx. 21 MeV), paying attention to the possible overestimation of alpha production at forward angles. The analysis of this experiment is still ongoing.
Other systems of interest for possible applications will be discussed.
[1] Phys. Rev. C 93 (2016) 041602(R).
[2] Nucl. Phys. A 709 (2022) 467.
[3] Rep. Prog. Phys. 62 (1999) 395.
[4] Phys. Rev. C 84 (2011) 044604.
[5] Phys. Rev. C 87 (2013) 064603.
[6] Phys. Rev. Lett. 110 (2013) 142701.
[7] Phys. Rev. C 88 (2013) 014327.

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A Target Design Laboratory for Nuclear Astrophysics Experiments

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Nuclear astrophysics is at the frontier between nuclear physics and astrophysics aiming to understand the creation of the elements in the universe. Nuclear reaction networks require the input from nuclear cross sections, which have to be determined experimentally by mimicking conditions similar to the ones encountered in the stars that is experiments in the low energy spectrum (generally below 10 MeV).

Although not generally at the center of a nuclear reaction experiment, target properties and characteristics are crucial for the ultimate success of any cross section measurement. With the goal of interacting with the end-user, aiming at the best possible reaction target production, we created the Target Design Laboratory (TDL) at LIP-Lisbon in Portugal. We have specialised ourselves in the production and characterisation of thin films with thicknesses in the order of hundreds of micrograms cm^{-2}, which are very suitable for many low-energy cross-section measurements.

In this contribution, I will present the current equipment available for target production at the TDL group; introduce the various techniques we have in-house and close-by for thickness and homogeneity characterization, and will discuss some examples of targets produced in the recent years for low-energy reaction experiments, with strong focus on nuclear astrophysics studies.

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Beyond the Barrier: Exploring α-Nuclear Potentials with Exotic Heavy Nuclei

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The poor knowledge of the α-nuclear potential in unstable nuclei still dominates the uncertainties associated to the production of the heavy p-nuclei [1,2]. Calculations of the elastic scattering cross section at energies close to the Coulomb barrier based on global α-nucleus potentials differ up to a factor of 2 when moving towards unstable nuclei with higher proton-to-neutron ratios. The lack of experimental data in the region around the heavy p-nuclei does not contribute to solve this issue.

In this talk I will present the first measurement of the elastic scattering of α-particles on exotic heavy nuclei, concentrating on the Sn isotopic chain. The experiment, performed at the HIE-ISOLDE facility at CERN, profited from the use of innovative thin silicon films with high amounts of He [3] and the high intensity beams for the isotopes 108, 109 and 110-Sn produced at ISOLDE. In addition to the astrophysical context of the measurement, I will present the main properties of the films, introduce the experimental setup considered for the measurement, and will show the current status of the analysis performed to the data obtained. The results from this benchmark measurement will open the door to the study of α-nuclear potentials in exotic proton-rich nuclei, contributing to the reduction of the uncertainties in network calculation studies.

References:
[1] A. Simon, et al. J. Phys. G 44, 064006 (2017)
[2] W. Rapp, et al. Astrophys. J. 653, 474 (2006).
[3] V. Godinho, et al. ACS Omega 1(6), 1229 (2016).

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Experimental study of ^{6}He Coulomb breakup as an indirect measurement of ^{4}He$(2n, \gamma)^{6}$He reaction rate for the astrophysical r-

process

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Compact binary mergers as Binary Neutron Star Mergers (BNSM) have attracted a lot of attention in recent years as the most likely site for r-process (rapid neutron capture) nucleosynthesis [1] and for the emission of gravitational waves [2]. Recently there has been reported experimental evidence of r-process nucleosynthesis in a BNSM identified as the origin of the gravitational-wave source GW170817 [3]. The nuclear reactions that describe the evolution of such systems involve thousands of nuclides following a complex network of capture and decay processes. Here, the main parameter determining the feasibility of the astrophysical environment to produce heavy elements by the r-process is the neutron-to-seed ratio (existing nuclei in the onset of the r-process, like ^{12}C). In this context, the three-body capture reaction ^{4}He$(2n,\gamma)^6$He are expected to be important in producing ^{12}C, thus playing a relevant role [4].
As part of a possible path to synthesize ^{12}C, a low mass seed nucleus of the r process, the collaboration has proposed the measurement of the ^{4}He$(2n,\gamma)^6$He reaction rate at the TriSol facility of the NSL laboratory at the University of Notre Dame [6,7]. The experimental approach adopted consists of measuring the Coulomb breakup channel in collisions of the system ^{6}He$+^{208}$Pb, that is, the ^{6}He$(\gamma,2n)^4$He reverse reaction, applying the theoretical framework described in [7], which was developed by members of the collaboration.
The experiment was performed in June 2013. The energy of the ^{6}He beam was 19.3 MeV. The detection system was composed of six silicon telescopes available at NSL placed at forward angles (11 ° < θ_{lab}< 25 °). A 1.7 mg/cm^2 thick self supported enriched target of ^{208}Pb, made by the collaboration at the target laboratory in the University of Lisbon-LIP, was used. More details about the experimental setup and preliminary results of the undergoing data analysis of the experiment will be presented in this talk.

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[1] Astrophys. J. 807, 115 (2015)
[2] Phys. Rev. Lett. 116, 061102 (2016)
[3] Nature 551, 67–70 (2017)
[4] Phys. Rev. C 74, 015802 (2006)
[5] NIM A 1047 (2023) 167784
[6] NIM B 541 (2023) 216-220
[7] Phys. Rev. C 93 (2016) 041602(R).