Developing system arrays for new experimental approach in nuclear astrophysics

G.L. Guardo[1], D. Lattuada[1,2], T. Petruse[3,4] on behalf of ASFIN & ELISSA collaborations

[1] INFN-Laboratori Nazionali del Sud, Catania, Italy
[2] Universitá degli Studi di Enna 'Kore', Enna, Italy
[3] Extreme Light Infrastructure Nuclear Physics/IFIN-HH, Magurele, Romania
[4] Scoala Doctorala de Ingineria si Aplicatiile Laserilor si Acceleratorilor, Universitatea Politehnica, Bucuresti, Romania

E-mail: guardo@lns.infn.it

Abstract. The advent of facilities providing high-intensity and high-resolution gamma ray beams and/or ultra-short and high-repetition laser pulses can potentially open a new path of astrophysical research. Indeed, a pencil size gamma beams with tunable energies from few keV up to tens MeV will offer distinctive chances to conduct precise measurements of small cross sections (on the scale of μb or even smaller) pertaining to nuclear reactions in the field of astrophysics. Consequently, it provides essential data for modeling astrophysical S-factors crucial to stellar evolution. On the other hand, the possibility to mimic the stellar conditions by laser-matter interaction generating a controlled laboratory plasma with thermodynamical status not too different from stellar conditions will open the way for the study of nuclear reactions of utmost importance for nuclear astrophysics.

For photonuclear reactions with astrophysical significance, as photodissociations occur at photon energies slightly above particle emission thresholds due to typical stellar temperatures, the resulting fragments possess low energies spanning from a few hundred keV to a few MeV. Consequently, detectors with low thresholds become imperative in such cases. Also, in the case of laser-induced reactions, in order to detect the fusion products and to measure the laser-accelerated ion distribution a proper system of detection is needed. Depending on the available exit channels of the nuclear reaction of interest, both charged particles and neutrons are foreseen.

Here, we present the Asfin's efforts on developing new detectors arrays suitable for the experimental requirements in these challenging measurements. Indeed, an experimental campaign is ongoing in order to test the feasibility of excitation functions and angular distributions determinations using versatile silicon strip arrays (namely LHASA and/or ELISSA). Moreover, extensive studies and simulations will be presented regarding the developing of a dedicated detection system comprising a cryogenically cooled supersonic nozzle, an appropriate interaction chamber, an array of neutron and charged particle detectors and two compact ion spectrometers for performing systematic study of laser-induced nuclear fusion reactions.

1. Introduction

Photodissociation reactions are of great importance in nuclear astrophysics. They involve the breaking of a nucleus into two or more fragments by the absorption of a photon. These reactions are crucial in the synthesis of heavy elements in the universe, as they can lead to the production of lighter elements that can then undergo additional fusion reactions to form heavier elements [1].

Among the others, in stellar explosive scenarios like type II supernovae, the p-process stands as a significant mode of nucleosynthesis responsible for generating stable nuclides beyond iron that are highly depleted in neutrons. These neutron-deficient nuclides are unattainable through the *s*- and *r*-processes. These particular nuclei are denoted as *p*-nuclei, with the designation "p" indicating their higher proton count compared to other stable isotopes of the same element [1]. As a group, the *p*-nuclei are the rarest among the stable nuclides. It is thought that these nuclides are synthesized by photodisintegration of pre-existing *s*- and *r*-nuclei. There are 35 nuclides classified as the *p*-process nuclides ranging from ^{74}Se to ^{196}Hg that are bypassed by the *s*- and *r*-process [2, 3]. Except for a few cases, there is a lack of data regarding photodissociation reactions that result in the creation of *p*-nuclei, necessitating the use of Hauser-Feshbach calculations. However, the final abundances of *p*-nuclei obtained from type II supernovae are highly sensitive to different prescriptions of the Hauser-Feshbach model. This sensitivity introduces significant systematic errors, potentially causing inaccurate and misleading comparisons between models and observational data. As a result, pinpointing the correct site for the *p*-process and comprehending *p*-process nucleosynthesis becomes challenging [4].

For example, *p*-nuclei of Mo and Ru are produced only by *p*-process in the scenario of supernova explosion. Astrophysical simulations indicate a consistent underproduction in the nucleosynthesis of $^{92;94}$Mo and $^{96;98}$Ru when comparing predicted abundances to their observed counterparts in the Solar System composition. Addressing this unresolved issue in *p*-process nucleosynthesis is anticipated through experimental determination of astrophysical reaction rates around Mo and Ru. [5].

Other important photodissociation reactions include the photodissociation of light nuclei such as deuterium, helium-3 and lithium-7. These reactions can contribute to the production of heavier elements through subsequent fusion reactions [6]. Additionally, photodissociation reactions can be used to study the properties of atomic nuclei, such as their energy levels and decay modes, providing valuable information for nuclear physics research [7].

Overall, photodissociation reactions are a crucial aspect of nuclear astrophysics, playing a key role in the production of the elements and providing a valuable tool for studying the properties of atomic nuclei. With the development of new technological facilities capable of generating high-intensity and high-resolution gamma ray beams, as well as ultra-short and high-repetition laser pulses, there is a potential for a new era of astrophysical research to be opened up [8, 9].

From another point of view, low-energy nuclear physics plays a critical role in two major fields of study: astrophysics and applied (plasma) physics. In astrophysics, it is crucial in determining the primordial abundances in Big Bang Nucleosynthesis (BBN) models, while it can also help in explaining the abundance of elements in the universe [10]. In applied physics, low-energy nuclear physics is significant because it operates in the energy range that is of interest for the design and operation of future fusion power plants [11]. Over the years, both direct and indirect measurements of the cross-sections for these reactions have been conducted. Some of these measurements propose that the presence of electrons, leading to a screening potential, can reduce the Coulomb barrier between the projectile and target nuclei at extremely low energies. This reduction results in an enhanced cross-section compared to interactions with bare nuclei and those occurring in astrophysical plasmas [10, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24].

A different approach is to mimic the stellar conditions by generating a controlled laboratory plasma with thermodynamical status not too different from stellar conditions. This paradigm has long been obstructed by the lack of proper technology, but with the advent of new techniques in laser amplification, many laboratories are starting to study how to create plasmas with temperatures and pressures close to those that exist only in the cores of stars [25, 26].

Considering these fields of experimental opportunities, challenges often arise when conducting experiments under demanding conditions. In the next paragraphs, we aim to showcase the efforts of Asfin in developing new detector arrays specifically designed to meet the requirements of these challenging measurement conditions and highlight their potential to enhance the accuracy and efficiency of experimental measurements in these challenging environments.

2. Nuclear Astrophysics with γ beam

In a general context, the study of photodissociation reactions is relatively more straightforward due to the phase space factor amplifying the (γ,p) and (γ,α) cross sections compared to the inverse process. This is particularly true when a high-quality gamma beam, such as the one available at the HIγS facility or soon to be accessible at the ELI-NP facility, is employed. For photonuclear reactions of astrophysical relevance, photodissociations occur at photon energies slightly above particle emission thresholds due to the typical temperatures in stars. Consequently, the resulting fragments have low energies ranging from a few hundred keV to a few MeV. Moreover, to gain a comprehensive understanding of the reaction mechanism, it is crucial to measure excitation functions and angular distributions over a wide range. Considering the potential presence of beam-induced background at forward angles, it is imperative to achieve the broadest possible angular coverage to ensure a sufficiently large range for effective nuclear spectroscopy.

As most reactions involve charged particles in the exit channel, the use of low-threshold detectors is essential. However, conventional particle identification techniques, like measuring energy loss in a thin detector or employing pulse shape analysis, have proven currently unattainable. Additionally, the adoption of a compact device, while advantageous for easy integration with ancillary detectors such as neutron arrays, renders the use of time-of-flight (ToF) for particle identification unfeasible. Given these limitations, kinematical identification emerges as the sole viable option presently, as highlighted by [27]. This approach necessitates high angular and energy resolution to effectively discriminate between various reaction kinematics, enabling the separation of the reaction of interest from others.

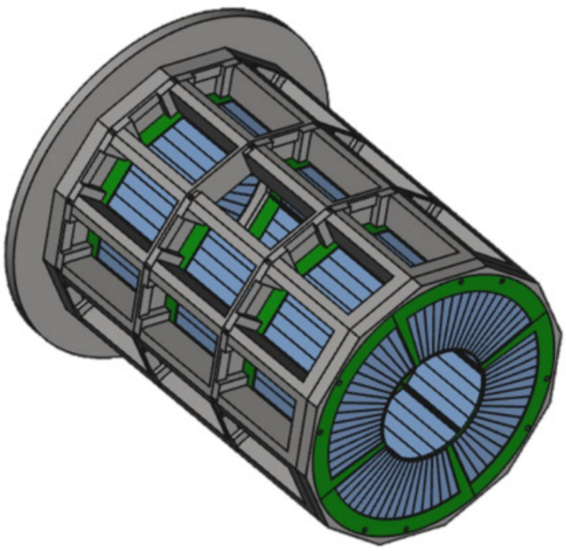

Figure 1. Full design of the ELISSA detector. It will be made of n. 3 rows of PSD detectors to form a barrel plus n. 8 end cap detectors to extend the angular coverage.

For all these reasons, silicon detectors represent one of the best solution for the construction of a dedicated array for a number of reasons: (i) they guarantee exceptional energy resolution, (ii) they have almost 100% efficiency in charged particle detection, (iii) thresholds can be set to very small values, (iv) they are not sensitive or very little sensitive to neutrons, gamma rays, electrons and positrons, which would constitute the beam induced background. Finally, silicon strip detectors would couple enhanced angular and energy resolution with high detection efficiency [28, 29]. High granularity is not a crucial aspect as a low counting rate is expected, making the probability of multiple hit very small.

Thus, the Extreme Light Infrastructure Silicon Strip Array (ELISSA) is under development in a common effort between the Asfin group from LNS-INFN and the Nuclear Astrophysics group of ELI-NP [30]. The full array will consist of 3 rings of 12 X3 position-sensitive detectors produced by Micron Semiconductor Ltd. [31], in a barrel like configuration, ensuring a total angular coverage in the laboratory system of about 100°. The angular coverage is extended down to about 20° (160° at backward angles) by using end cap detectors such as the assembly of four QQQ3 segmented detectors by Micron Semiconductor Ltd. [31]. A sketch of the final expected setup is shown in Fig. 1. The central ring contains only 11 detector in order to permit the positioning of the target in the middle of the detector holder, so that the total number of X3 detectors is 35. In order to ensure the maximum versatility in terms of physical cases, ELISSA project will provide two different detector thickness: 300μm and 1000μm [32]. The X3 is a 4-strip detector, 4 cm wide, position sensitive along the longitudinal axis (7.5 cm long), leading to a position resolution better than 1mm around 10 MeV, while QQQ3 is a segmented detector with 16 radial segments (3 mm pitch) and 16 angular segments, with inner and outer radii of 4.91 and 10 cm and 1000μm thick.

Another array was already developed at LNS-INFN in Catania (Italy) and it is called Large High-resolution Array of Silicon for Astrophysic (LHASA). LHASA (Fig. 2) consists of six YY1 silicon strip detectors with a thickness of 300 μm mounted in a lamp-shade configuration and optimized to detect alpha particles in a wide angular range.

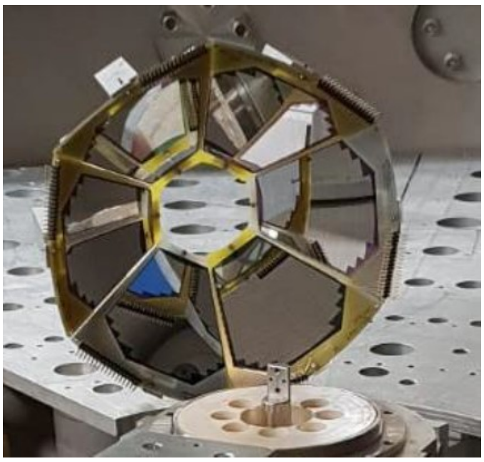

Figure 2. The LHASA detector mounted inside a scattering chamber.

2.1. Experimental test

In the framework of developing, testing and commissioning the silicon arrays described in the previous section, we proposed and studied some direct cross section measurements of interest for nuclear astrophysics and very suitable for pointing out the experimental feature of our detectors. Here in the following a brief description of those experiments:

2.1.1. The $^{7}Li(\gamma,t)^{4}He$ cross section measured with a LHASA like detector The ^{7}Li(γ,t)^{4}He ground state cross section was measured for the first time using monoenergetic γ rays at the High Intensity Gamma-ray Source (HIγS) due to its importance for the primordial Li problem [33, 34]. Although over the last 30 years most measurements of the inverse ^{3}H(α,γ)^{7}Li reaction have concentrated in an energy range below E_{γ} = 3.65 MeV [35, 36, 37, 38], measurements at higher energies could potentially restrict the extrapolation to astrophysically important energies. The experiment was carried out using the large area annular silicon detector array (SIDAR), very similar to the proposed LHASA. A detailed description of the experimental approach, data analysis and astrophysical results can be found here [39]. The results of this experiment clearly prove that photodisintegration cross sections can be determined with good accuracy using a large-area silicon detector array, pushing for the development of ELISSA and LHASA detectors.

2.1.2. Direct measurement of the $^{19}F(p,\alpha)^{16}O$ reaction cross section The ^{19}F(p,α)^{16}O reaction is an important destruction channel in Asymptotic Giant Branch (AGB) stars and plays a significant role in the nucleosynthesis of heavy elements in the Universe [40]. To better understand the astrophysical implications of this reaction, an experimental campaing was conducted using ELISSA coupled with LHASA, forming a silicon detector array with high angular coverage and extraordinary angular and energy resolution. A first experiment was performed at INFN – Laboratori Nazionali del Sud, Catania (Italy) using the 15 MV Van der Graaf Tandem that provided a ^{19}F beam with an energy range from 9 up to 18.5 MeV. A comprehensive account of the experimental method, analysis of the data, and astrophysical findings can be retrived here [41]. A second experiment focused on the ^{19}F(p,α_{π})^{16}O and ^{19}F(p,α_{γ})^{16}O reaction channels was recently performed at IFIN-HH, Magurele (Romania) using the 3 MV Tandetron accelerator that provided a ^{19}F beam spanning an energy range from 7 to 15 MeV with a similar approach of the previous experiment. In this case the detection setup consisted of one ring of ELISSA (12 Micron X3 position sensitive silicon strip detectors of 1000 μm thick) and LHASA (5 Micron YY1 silicon strip detectors of 300 μm thick [31]). The high precision of the ELISSA and LHASA detector system will allow for a detailed study of the angular distribution of the emitted α particles, which provides insights into the reaction mechanism and the factors that determine the cross section. The analysis is still ongoing.

3. Nuclear Astrophysics with laser beam

The study of nuclear reactions in laboratory has always been hindered by the very low cross-sections values at energies of astrophysical interest (1-100keV). This leads nuclear astrophysicists either to build huge and expensive underground laboratories where to perform long experiments with low and controlled background (LUNA [42], JUNA [43]), or to exploit indirect methods usually involving nuclear-structure models such as the Trojan Horse Method (THM [44]) or Asymptotic Normalization Coefficient (ANC [45]). Both approaches have proven to be successful to a great extent; nevertheless, plasma in stellar objects is a very different state from the solid or gas targets commonly used in standard nuclear physics experiments involving conventional accelerators. It is well known that the plasma state affects in a non-negligeable way many nuclear processes, such as electron screening in fusion reactions and Non-Local Thermodynamic Equilibrium effects in beta decays.

Our current knowledge on laser-matter interaction, nurtured by the recent developments in laser pulse amplification, provides a scenario where the interplay between the laser intensity (in the regime above 10^{6} W/cm^{2}) and the target composition (thickness and structure) holds a key role in determining the paradigm of the ion acceleration and its scale [46]. Among the others, the interaction of a material prepared at a thermodynamic state close a critical point (i.e., where matter coexists in different states, thermodynamically close to phase shifts) with lasers shows a more intense interaction with respect to conventional materials such as gas or solid and results in super-hot matter and higher laser absorption, finally forming plasmas with multi-keV temperature alongside strong EMP and x-ray emission [47]. These energies overlap with the typical temperatures of stellar cores where thermonuclear reactions occur, thus making this paradigm a perfect scenario for nuclear astrophysics research.

In particular, the interaction of ultra-short laser pulses with an expanding gas mixture at controlled temperature and pressure inside a vacuum chamber has been demonstrated the formation of molecular clusters that maximizes the laser absorption, causing the full strip of the electrons of the gas [48, 49, 50]. The sudden onset of a positive space charge triggers the Coulomb dissociation of the clusters resulting in multi-keV ion acceleration with a nearly isotropic emission (Coulomb Explosion, CE). The accelerated ions interact in the surrounding plasma and nuclear reactions take place. By measuring the ion energy distribution and detecting the products of the occurred nuclear reactions, it is possible to infer important information on the cross section of the nuclear reactions of interest [51, 52].

3.1. The VALAR project

The systematic study of laser-induced nuclear fusion reactions using the Coulomb Explosion paradigma obviously requires a dedicated system as the one that is now under development at INFN - Laboratori Nazionali del Sud in Catania (Italy). The Versatile Array for Laser-induced Astrophysics Research (VALAR) will consist of (i) a cryogenically cooled supersonic nozzle, (ii) an appropriate interaction chamber, (iii) an array of neutron and charged particle detectors and (iv) two compact ion spectrometers.

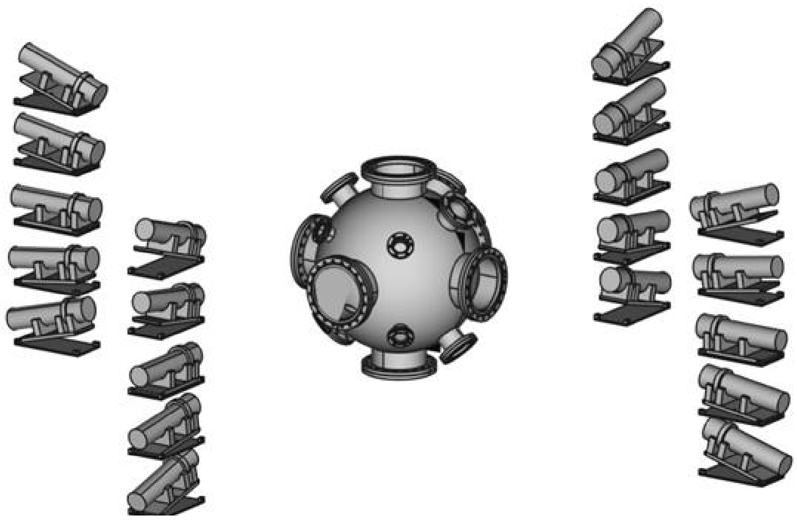

Figure 3. Schematics view of the valar neutron array with prototype supports and chamber.

In particular, the VALAR detection system will be optimized to detect the fusion products and to measure the laser-accelerated ion distribution. Depending on the available exit channels of the nuclear reaction of interest, both charged particles and neutrons are foreseen. For the latter, the use of both plastic and liquid scintillators in Time of Flight (ToF) configuration proved to be an excellent choice owing to their linear and fast response coupled to simple electronics. On the other hand, the detection of both the fusion products and the primary accelerated protons, alpha particles and light ions are obstructed by the high electromagnetic background induced by the interaction of high-power laser pulses with the target together with the concurrent generation of a strong EMP signal. For this reason, fast detectors with high radiation hardness, such as Silicon Carbides (SiC [53]) and Polycrystalline CVD Diamonds [54] in ToF configuration are perfect candidates for charged particle detection. A schematic view of the final configuration of the VALAR array is reported in fig. 3.

3.2. The deuterium-deuterium nuclear fusions as test-case

The deuterium burning has been chosen for the VALAR commissioning thanks to the recent history of successful experiments with deuterium clusters irradiated by high-power laser pulses [55]. Moreover, the importance of deuterium burning is twofold: it is crucial for the Big Bang Nucleosynthesis, since it represents the most crucial reaction in this scenario and it is a reference for the power plants applications. In addition, very few data are available below 15 keV and the inferred electron screening potential from direct measurements is significantly larger than the adiabatic limit [56].

A preliminary experiment was performed using the Texas Petawatt laser (TPW) which delivered 150-270 fs pulses at 1057 nm wavelength and energy ranging from 90 to 180 J to D_2 or CD_4 molecular clusters. The detection setup consisted of five EJ-232Q and EJ-200 plastic scintillation detectors forming a prototype of the final VALAR detection array. In this experimental setup, a highly concentrated laser beam is directed at a gas mixture containing D_2 clusters and ^{3}He atoms. The intense electromagnetic field of the laser temporarily strips away the electrons from the clusters, which are generated during the rapid expansion from the nozzle. This action results in the acceleration of deuterium ions, triggered by the abrupt emergence of the repulsive Coulomb potential attributable to their positive charges. Consequently, ions with multi-keV kinetic energies are generated through this process known as Coulomb explosion. These deuterium ions can collide with each other and generate d+d fusion reactions or they can collide with deuterium atoms at rest in the gas jet outside the focal volume. ^{3}He atoms do not absorb the laser energy efficiently because they do not form clusters at 86 K, but an energetic deuterium ion can collide with a cold ^{3}He atom resulting in d+^{3}He fusion reaction. A detailed description of the data analysis can be found here [57]. By measuring the plasma distribution, its volume, ion concentration, density and the number of fusions occurring for each reaction, in this case we were able to derive the S-factor without any model assumption and compare it with other experiments finding a good agreement with conventional beam-target data within the experimental error. These studies successfully demonstrate the reliability of the technique and opened the way for the study of other reactions of utmost importance for nuclear astrophysics and applied research such as the proton-boron, deuterium-tritium, deuterium-^{3}He, ^{12}C-^{12}C, ^{16}O-^{16}O fusion reactions.

4. Conclusions

The emergence of high-intensity and high-resolution gamma-ray beam facilities presents a significant opportunity for nuclear physics and astrophysics. These facilities enable the measurement of reactions of primary astrophysical significance that were previously inaccessible, marking a pioneering step in advancing our understanding of these phenomena. At the same time, the advent of high-power and high-repetition rate lasers open the way for systematic studies of nuclear astrophysics reaction in plasma with stellar-like conditions.

To catch these new experimental opportunities, the Asfin group is developing new arrays with peculiar characteristics: high-resolution, low-threshold, high-efficiency, compactness, etc. Preliminary results on methods and arrays make us confident for the new perspectives and open the way for new experimental campaigns.

References

[1] C. Iliadis, *Nuclear Physics of Stars*, (Weinheim, Wiley-VCH Verlag, 2007)
[2] T. Rauscher, N. Dauphas, I. Dillmann, C. Fröhlich, Z. Fülöp, and G. Gyürky, 2013 *Rep. Prog. Phys.* **76**, 066201.
[3] M. Pignatari, K. Göbel, R. Reifarth, and C. Travaglio, 2016 *Int. J. Mod. Phys. E* **25**, 1630003.
[4] W. Rapp et al., 2005 *Nucl. Phys. A* **758**, 545.
[5] H.Y. Lan et al., 2022 *Phys. Rev. C* **105** 044618.
[6] M. La Cognata et al., 2017 *J. of Inst.* **12** C03079.
[7] N. Pietralla, J. Isaak, and V. Werner, 2019 *Eur. Phys. J. A* **55**, 237.
[8] D. L. Balabanski et al., 2017 *EPL* **117**, 28001.
[9] D. Filipescu et al., 2015 *Eur. Phys. J.* **A 51**, 185.
[10] A. Tumino et al. 2014, *Astroph. J.* **758**, 96.
[11] H. Hora et al., 2017, *Laser and Particle Beams* **35**, 730.
[12] The First Research Group, 1985 *Chinese J. of Nucl. Phys.* textbf9, 723.
[13] D. S. Leonard, H. J. Karwowski, C. R. Brune, B. M. Fisher, and E. J. Ludwig 2006, *Phys. Rev. C* **73**, 045801.
[14] R. L. Schulte, M. Cosack, A. W. Obst, and J. L. Weil, 1972 *Nucl. Phys. A* **192**, 609.
[15] R. E. Brown and N. Jarmie, 1990 *Phys. Rev. C* **41**, 1391.
[16] U. Greife, F. Gorris, M. Junker, C. Rolfs, and D. Zahnow, 1995 *Z. Phys. A* **351**, 107.
[17] A. Krauss, H. W. Becker, H. P. Trautvetter, C. Rolfs, K. Brand, 1987 *Nucl. Phys. A* **465**, 150.
[18] M. La Cognata et al., 2005 *Phys. Rev. C* **72**, 065802.
[19] M. Aliotta et al., 2000 *Eur.Phys.J. A* **9**, 435.
[20] U. Schroeder, S. Engstler, A. Krauss, K. Neldner, C. Rolfs, E. Somorjai, K. Langanke, 1989 *Nucl. Instr. Meth. B* **40**, 466.
[21] S. Kimura, A. Bonasera, 2005 *Nucl. Phys. A* **759**, 229.
[22] T. D. Shoppa, S. E. Koonin, K. Langanke, R. Seki, 1993 *Phys. Rev. C* **48**, 837.
[23] S. Kimura and A. Bonasera, 2004 *Phys. Rev. Lett.* **93**, 262502.
[24] G. Shaviv and N. Shaviv, 2000 *Astrophys. J.* **529**, 1054.
[25] D. Strickland and G. Mourou, 1985 *Optics Communications*, **55**, 447.
[26] A. J. Kemp, S. C. Wilks, E. P. Hartouni, and G. Grim, 2019 *Nature Communications*, **10**, 4156.
[27] D. Lattuada et al., 2017 *EPJ Web Conf.* **165**, 01034.
[28] S. D. Pain et al., 2007 *Nucl. Instr. Meth. Phys. Res.* **B 261**, 1122.
[29] M. Matos et al., 2010 **PoS NIC XI**, **226**.
[30] G. L. Guardo et al., 2017 *EPJ Web of Conf.* **165**, 01026.
[31] Micron Semiconductor, General catalogue, http://www.micronsemiconductor.co.uk/pdf/cat.pdf
[32] S. Chesnevskaya et al., 2018 *J. of Inst.* **13**, T05006.
[33] B. D. Fields, 2011 *Annu. Rev. Nucl. Part. Sci.* **61**, 47.
[34] A. Coc et al., 2014 *J. Cosmol. Astropart. Phys.* **10** 50.
[35] R. H. Cyburt et al., 2008 *JCAP*, **11** 12.
[36] P. Descouvemont et al., 2004 *At. Data Nucl. Data Tables* **88** 203.
[37] C. R. Brune, R.W. Kavanagh and C. Rolfs, 1994 *Phys. Rev. C.* **50** 2005.
[38] T. Neff, 2011 *Phys. Rev. Lett.* **106** 042502.
[39] M. Munch et al., 2020 *Phys. Rev. C* **101**, 055801.
[40] S. Cristallo et al., 2009 *Astroph. J.* **696**, 797.
[41] G. L. Guardo et al., 2023 *Eur. Phys. J. A* **59** 65.
[42] U. Greife et al., 1994 *NIM A* **350** 327.
[43] L. WeiPing et al., 2019 *Proc. IAU* **15** 313.
[44] A. Tumino et al., 2023 *Ann. Rev. of Nuc. and Part. Sc.* **71** 345.
[45] R. E. Tribble, C. A. Bertulani, M. la Cognata, A. M. Mukhamedzhanov, and C. Spitaleri, 2014 *Rep. on Prog. Phys.* **77** 106901.
[46] G. A. Mourou, T. Tajima, and S. v. Bulanov, 2006 *Rev. of Mod. Phys.* **78** 309.
[47] T. Tajima, Y. Kishimoto, and M. C. Downer, 1999 *Phys. of Plasmas* **6** 3759.
[48] K. W. Madison, P. K. Patel, M. Allen, D. Price, R. Fitzpatrick, and T. Ditmire, 2004 *Phys. Rev. A* **70** 053201.
[49] W. Bang et al., 2013 *Phys. Rev. Let.* **111** 055002.
[50] M. Barbui et al., 2013 *Phys. Rev. Let.* **111** 082502.
[51] W. Bang et al., 2013 *Phys. Rev. E* **88** 033108.
[52] H. J. Quevedo et al., 2018 *Phys. Let. A* **382** 94.
[53] S. Tudisco et al., 2018 *Sensors* **18** 2289.
[54] M. Cipriani et al., 2019 *J. of Inst.* **14** C01027.

[55] T. Ditmire, J. Zweiback, V. P. Yanovsky, T. E. Cowan, G. Hays, and K. B. Wharton, 1999 *Nature* **398** 489.
[56] Y. Xu, K. Takahashi, S. Goriely, M. Arnould, M. Ohta, and H. Utsunomiya, 2013 *Nuc. Phys. A* **918** 61.
[57] D. Lattuada et al., 2016 *Phys. Rev. C* **93** 045808.