Journal of Physics: Conference Series **2894** (2024) 012023 doi:10.1088/1742-6596/2894/1/012023

Nuclear Astrophysics Using Laser-Driven Neutrons

Takehito Hayakawa

National Institutes for Quantum Science and Technology, Kyoto 619-215, Japan
Institute of Laser Engineering, Osaka University, Suita 565-0871, Japan

E-mail: hayakawa.takehito@qst.go.jp

Abstract. Progress in laser physics has enabled us to produce various particles such as electrons, photons, and ions from high field plasma generated from the interaction between high power laser and materials. Neutrons could be generated by nuclear reactions on the second target behind the first target. At present, it is possible to generate neutrons with a flux of up to 10^{11} neutrons/shot. These neutrons are suitable for the study of nuclear astrophysics. We present the perspective and the present activity for the application to the nuclear astrophysics.

1. Introduction

Progress in laser physics has enabled us to accelerate various particles such as electrons, photons, and ions from the interaction between high power laser and materials [1]. These laser-driven particles have the remarkable features of continuous energy spectrum, brightness, and short pulse width. These features are suitable for the study of nuclear astrophysics [2]. The stellar nucleosynthesis occurs in high temperature environments such as T=10^{8-9} K. In such environments, particles including neutrons have a wide energy spread described by Planck or Fermi-Dirac distributions. Hayakawa et al. [2] have suggested that one generates a laser driven-particles having an energy spectrum similar to that in stellar environments and measures directly the integrated nuclear reaction cross sections using the laser-driven particles. A pioneering laser experiment was carried out using the Texas Petawatt Laser, where the cross sections of the ^{3}He(d, p)^{4}He nuclear reaction in a hot plasma were measured [3]. This measurement is important for understanding the Big-bang nucleosynthesis, and recently the ^{7}Li(d, n)^{8}Be reaction induced by the Shenguang-II laser has been studies [4].

Neutrons are also produced by high power laser [5, 6, 7, 8, 9]. Using laser-accelerated ions such as proton, neutrons could be generated via nuclear reactions on a secondary target located behind the primary target such as beryllium (Be). Deuterons are also accelerated from a deuterated carbon plastic (CD) target with high intense laser and thereby neutron are also produced by deuteron-induced reactions at the secondary target [10]. The maximum energies of neutrons generated by laser driven neutron sources (LDNSs) reach a few tens of MeV, but it is possible to decrease the neutron energies using a moderator around the second target to make the energy spectrum suitable for various applications [11]. At present, the yield of primary neutrons reaches more than 10^{10} neutrons/sr in the world [12, 13, 14, 15, 16].

In the universe, neutrons have an important role for synthesis of elements. Most elements heavier than the iron group have been predominantly synthesized by two neutron capture processes of slow neutron capture (s process) and rapid neutron capture (r process) in early generations of stars before the solar system formation. As shown in Fig. 1, the s process goes slowly along the β-stability line, where heavier isotopes are produced by neutron capture and when an unstable isotope is produced by neutron capture it decays to heavier elements by β^- decay. In contrast, the r process occurs in explosive astrophysical environments such as neutron star mergers or supernova explosion. The successive neutron capture and β^- decay occurs in short time in extremely neutron-rich regions. After the freeze out of the r process, the unstable isotopes decay to the stable isotopes through successive β^- decay. Thus, neutron capture cross sections on neutron rich unstable isotopes are one of the key parameters for understanding the r process, and an intense neutron source is required for the study of the r process. For the study of the r process, Habs et al. have proposed to generate neutron-rich isotopes using nuclear fusion-fission reactions with heavy ions accelerated by interactions between high intense laser and heavy element materials such as ^{232}Th [17]. Furthermore, Hill and Wu have proposed a novel method that neutron-rich isotopes being four neutrons heavier than an initial stable isotope are produced by successive neutron capture reactions with intense LDNSs [18]. To study the s process, nuclear experiments using high intense neutrons generated by laser D+T nuclear fusion reactions at the National Ignition Facility (NIF) has been proposed [19]. The neutron experiment is also useful for the study of the γ process [19]. In the γ process in supernovae, neutron-deficient stable isotopes are synthesized by successive (γ, n) reactions. Intense neutron sources could be used for the study of the γ process using the inverse reactions [19]. Furthermore, capture of secondary neutrons produced by nuclear reactions with high-energy galactic cosmic-rays occurs in the solar system. The effects of neutron capture have been observed in isotopic abundances in meteorites. The LDNS is also useful for the study of these phenomena.

These proposals and experimental demonstrations show that LDNSs have a large potential for the study of nuclear astrophysics, in particular, neutron capture reactions. In this paper, we present the recent progress in LDNSs at Osaka university for the study of laser nuclear astrophysics.

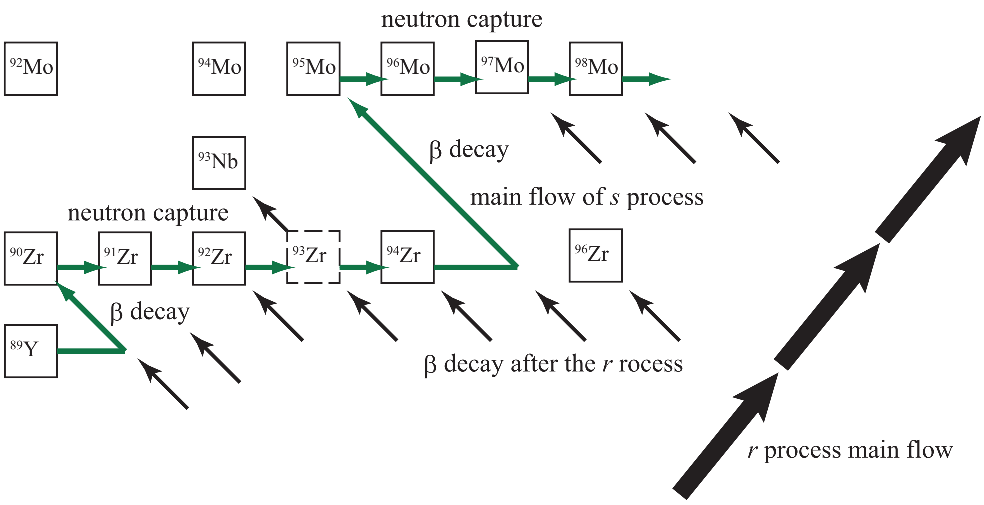

Figure 1. Schematic view of the nucleosynthesis flow of the s and r processes on athe partial nuclear chart.

2. High energy neutrons in astrophysics

One of the possible applications of fast neutrons with energies of a few or tens MeV is the study of decay acceleration, which signature has been observed of isotopic abundances of several elements in meteorites. A meta-stable isotope ^{176}Lu exists in the present solar system with an isotopic fraction of approximately 2.60%. It decays to its daughter nucleus ^{176}Hf with a half-life of (3.719±0.007)×10^{10} y [21], where the 6$^+$ state in ^{176}Hf is predominantly produced and γ-rays with energies of 88, 202, 307, and 401 keV may be radiated. The ^{176}Lu-^{176}Hf system has a potential as a nuclear chronometer for evaluation of the age from a stellar nucleosynthesis event before the solar system formation to the present [22, 23] and the age of formation and evolution of planets and moon [24, 25]. Although the half-life values have been reported by many groups, the half-life has not been established before the last study [21]. The half-life of ^{176}Lu was also evaluated from the Lu-Hf isochron methods of meteorites and terrestrial rocks. First, the age of the formation of a sample should be determined using another chronometer such as the U-Pb system. Second, the isotopic abundances of the Hf and Lu elements are precisely measured, and the half-life of ^{176}Lu could be determined by these data. The half-life of approximately 3.72×10^{10} y was reported for terrestrial rocks and some meteorites [26, 27]. However, different half-lives around 3.51×10^{10} y were provided from the analyses of several meteorites [25]. This discrepancy has been unresolved problem and several models for different half-lives have been proposed [28].

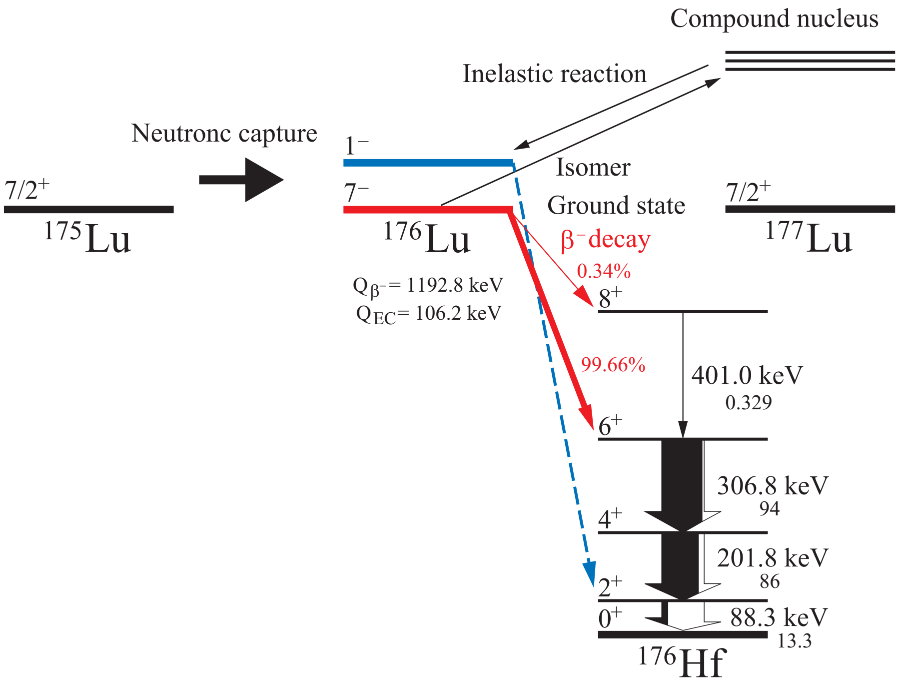

Figure 2. Figure caption for a narrow figure where the caption is put at the side of the figure.

One of the proposed models is decay acceleration by cosmic γ-rays with energies from a few hundreds keV to a few MeV. There is a β-unstable isomeric state at 123 keV, which decays to an excited state at 88 keV on the daughter nucleus ^{176}Hf. When the mete-stable ^{176}Lu isotopes are irradiated by γ-rays, they are exited states on ^{176}Lu and a part of the excited states decay to the isomer by γ-ray radiation and subsequently decays to ^{176}Hf with a half-life of approximately 3.6 h. This model can explain the decay acceleration by cosmic-ray radiation in the early solar system. As the γ-ray sources, various models such as supernova explosion nearby the proto-solar system have been considered. When such process occurs, the isotopic abundance of ^{176}Lu relative to the stable isotope ^{175}Lu should decrease. However, the recent analysis of Lu isotopes in meteorites, where the decay acceleration was observed, shows that the isotopic abundance ratio ^{176}Lu/^{175}Lu has not been changed. In such situation, Hayakawa et al. [21]

Journal of Physics: Conference Series **2894** (2024) 012023 doi:10.1088/1742-6596/2894/1/012023

have proposed another model that the decay acceleration was induced by high energy neutrons generated by nuclear reactions with high-energy galactic cosmic rays (see Fig. 2). The ^{176}Lu decay is accelerated by the inelastic scattering with neutrons with energies from 123 keV to a few MeV. A neutron incident on ^{176}Lu may form a compound nucleus ^{177}Lu, which decays to an exited state on ^{176}Lu through neutron emission in neutron inelastic scattering and subsequently the exited state may decay to the short-lived isomer in ^{176}Lu. In this process, ^{176}Lu and the isomer of ^{176}Lu are newly produced by neutron capture on the stable isotope ^{175}Lu with neutrons in wide energy range from thermal energy to a few MeV. Thus, this model is not inconsistent with the result for the ^{176}Lu/^{175}Lu ratio measurement. However, there is few experimental data for the cross section of the neutron inelastic reaction of ^{176}Lu(n, n')^{176}Lu^{m}.

Neutrons generated by laser is suitable for measurements of the inelastic reaction cross sections. For the cross section measurement, the accurate neutron flux should be provided. In general, the neutron energy spectrum and flux in the LDNS experiment have been evaluated using the time-of-flight (TOF) method [20]. To verify the accuracy of the TOF method, Mori et al. [29] measured the flux of high energy neutrons provided from high power laser using an activation method. The activation method has been known as one of the methods for precise measurement of the number of nuclides generated by a nuclear reaction and its cross sections. The experiment was carried out using the petawatt laser for Fast Ignition Experiments (LFEX) laser system at the ILE, Osaka University. In LFEX experiments, four laser pulse with an intensity of approximately 1×10^{19} W/cm^2 with a width of 1.5 ps in half width at half maximum (FWHM) were focused on a deuterated carbon plastic target with a thickness of 1.5 μm. A laser shot without any Be targets was used for the measurement of the energy spectra of laser accelerated ions. Protons and deuterons were generated via the Target Normal Sheath Acceleration mechanism. The energy spectra of the protons and deuterons were measured by a Thomson parabola ion spectrometer. The protons and deuterons were accelerated up to 30 MeV/u and 10 MeV/u, respectively, with continuous energy. After this shot, a cylindrical Be target with a diameter of 5 mm and a height of 10 mm was inserted behind the primary target to generate high energy neutrons and another laser shot was used for the activation experiment with neutrons. The neutrons were produced primarily by ^{9}Be(d, n) and ^{9}Be(p, n) nuclear reactions on the Be target and the energies of the neutrons were in the range from a few hundreds keV to a few tens MeV. The activation targets were placed behind the Be target. The four type of materials were used as the activation targets. They are Hf+Zr alloy (Hf=99.9%) and Au (99.95%) discs with a diameter of 9 mm and a thickness of 1 mm, Mn shots with a total volume of approximately 124 mm^3 with an isotopic fraction of 99.999%, and Co shots of 99.98% fraction and approximately 125 mm^3 were used. To compare the energy spectrum, a TOF measurement was carried out using a benzophenon-doped BBQ liquid scintillation detector with a size of ϕ60 mm×60 mm with a photomultiplier tube (PMT), which was located approximately 8.3-m downstream from the neutron source. The wave signals from the PMT were recorded using an oscilloscope by shot by shot, and the the neutron energy spectrum for each laser shot was evaluated from each recorded wave.

After laser shot to generate neutrons, the activation targets were moved to the detection position. An unstable isotope ^{196}Au with a half-life of approximately 6.2 d was produced by the ^{197}Au(n, 2n)^{196}Au nuclear reaction, and another unstable isotope ^{198}Au with a half-life of 2.7 d was produced by neutron capture on ^{197}Au. The unstable isotope ^{56}Mn with a half-life of 2.6 h was produced by the ^{55}Mn(n, γ)^{56}Mn reaction. There are many stable isotopes in Hf so that some unstable Hf isotopes and isomers were produced. The γ-rays from the activation targets were measured with high-purity germanium (HPGe) detectors with detection efficiencies of 30−70% relative to a 3 inch×3 inch NaI(Tl) scintillation detector. The energy resolutions and detection efficiencies of the HPGe detectors were calibrated using standard sources of ^{60}Co, ^{133}Ba, and ^{152}Eu. The natural background radiations were shielded by lead blocks with a

Journal of Physics: Conference Series **2894** (2024) 012023 doi:10.1088/1742-6596/2894/1/012023

thickness of typically 10 cm and copper plates with a thickness of 5 mm. The signals from the HPGe detectors were recorded with a multichannel analyzer. The γ-rays from ^{180}Hf^{m}, ^{196,198}Au, and ^{56}Mn with the relatively short half-lives were measured for about twice time of their half-lives, respectively, whereas the γ-rays from ^{175,181}Hf, ^{54}Mn, and ^{58,60}Co with half-lives longer than 70 d were measured for about three months.

In general, the nuclear reaction cross section is a function of the energy of the incident particle. Thus, in the activation method we can obtain only the integrated reaction cross section with an assumed energy distribution, which is obtained by another method. The energy distribution obtained from the TOF measurement was used to estimate the integrated (n, 2n) reaction cross sections on the target nuclides. The integrated reaction cross section was obtained by the integration of the cross section with the neutron energy distribution. The number of the neutrons produced by the laser shot can be obtained by dividing the nuclear reaction rate on a nuclide by the integrated (n, 2n) reaction cross section of the nuclide. The results for the four elements are consistent within their uncertainties. This fact shows that this method is effective for evaluation of neutron flux in the MeV energy region. The average flux for the four results was $(5.4\pm0.5)\times10^8$ neutrons/sr, whereas the flux evaluated from the TOF method was $(6.1\pm1.2)\times10^8$ neutrons/sr. This result indicates that the well-calibrated TOF method is also useful for estimation of the neutron energy spectrum and the total neutron number.

3. Evaluation of thermal neutron flux

Thermal neutrons have important roles in various applications at present. Furthermore, it has been known that thermal neutron capture naturally occurs in the universe. The isotopic abundance anomalies in Cd, Sm, and Gd in lunar rocks, which was returned by the Apollo program, indicate that the bombardment of the lunar surface by neutrons produced by galactic cosmic-rays and the isotopic abundance was changed by thermal neutron capture [30]. This is because the thermal neutron capture cross section of ^{113}Cd, ^{149}Sm, or ^{155,157}Gd is larger than the other isotopes in the same element by 2$-$4 orders of magnitudes. Furthermore, the neutron capture was observed in Hf isotopes in "mesosiderite" meteorites, which are considered to come from the Vesta asteroid [31]. Thus, thermal neutrons generated from high power laser could contribute to study of these phenomena.

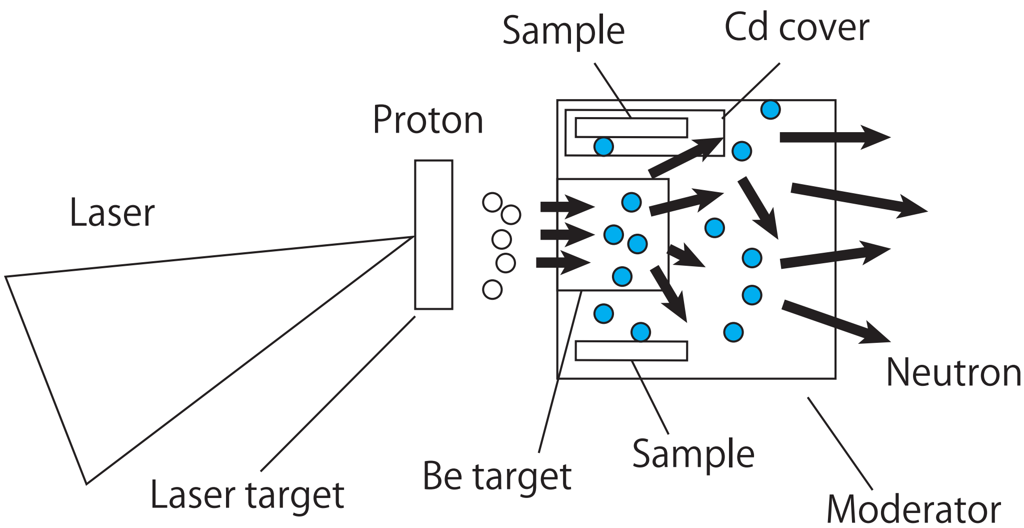

Figure 3. Schematic view of the nucleosynthesis flow of the s and r processes on athe partial nuclear chart.

The evaluation of the thermal neutrons generated by laser is also one of the key techniques for using thermal neutrons for applications. Mori et al. [32] evaluated thermal neutron flux using the cadmium differential method with activation. In this method, the neutron energy spectrum is assumed to have two components of thermal energy and epithermal energy. The two target sets were prepared. One of the two targets is directly irradiated by neutrons so that the neutron capture in the target originates from both of the thermal and epithermal neutrons. In contrast, the another target is set inside of a Cd shield for neutron irradiation to absorb thermal neutrons. Because the thermal neutron capture cross section of a stable isotope ^{113}Cd is as large as 20647 barn, most thermal neutrons were absorbed by Cd shields and the neutron capture is caused only from epithermal neutrons. From these two data, the fluxes of the thermal neutrons and epithermal neutrons can be obtained.

The experiment was carried out using the LFEX at the ILE in Osaka University. The four laser pulses with an intensity of 1.26×10^{19} W/cm^2 with a width of 1.5 ps in FWHM were focused on a target with a thickness of 5 μm. Protons and deuterons were accelerated up to 30 MeV/u and 10 MeV/u, respectively. After the energy measurements of the ions, the experimental setup was changed to produce thermal neutrons. A ^{9}Be block (ϕ5 mm$\times$10 mm) was placed at 2-mm distance behind the CD target. High energy neutrons at MeV were primarily produced from the Be target. A polyethylene moderator with a volume of 46 cm^3 and a density of 9.6 g/cm^3 was located around the Be target to decreases the neutron energies (see Fig. 3). The moderator consisted of two cylindrical parts and the Be target was hold in the front part. Metals of Hf ($\geq$97%) and Au (99.95%) discs (ϕ9 mm$\times$1 mm), Mn (99.999%, about 100 mm^3) shots, and Co (99.98%, about ϕ5 mm$\times$9.5 mm) pillars were used for the activation. These activation targets were placed around the Be target axisymmetrically to the laser axis and the distance between the activation targets and the Be target were approximately 9 mm. After a cooling time of 15 minutes from laser shot, the activated targets were moved to a position to measure γ-rays from the targets. The γ-rays were measured with HPGe detectors. The signals from the HPGe detectors were recorded with a multichannel analyzer. The reaction rates can be obtained by the following equations:

$$r_{\rm woCd} = \frac{A}{\varepsilon I_\gamma}\frac{M}{N_A\theta m}\left(e^{-\lambda t_1} - e^{-\lambda t_2}\right)^{-1} \tag{1}$$

and

$$r_{\rm wCd} = \frac{A'}{\varepsilon I_\gamma}\frac{M}{N_A\theta m'}\left(e^{-\lambda t'_1} - e^{-\lambda t'_2}\right)^{-1}, \tag{2}$$

where ε is the detection efficiency, I_γ is the γ-ray emission probability, M is the atomic mass of the target isotope, θ is the isotopic abundance of the target isotope, m and m' are the masses of the samples without and with the Cd cover, respectively, λ is the decay constant, t_1 and t'_1 are the measurement start time for the samples without/with the Cd cover, t_2 and t'_2 are the measurement finish time, and N_A is the Avogadro number. For the Cd differential method, the targets with and without a Cd shield were measured by the same HPGe detector to cancel out the systematic error caused by the detector system. The thermal neutron capture reaction rates $r_{\rm thermal}$ was given by $r_{\rm thermal} = r_{\rm woCd} - r_{\rm wCd}$ and the thermal neutron fluence $n_{\rm thermal}$ is given by $n_{\rm thermal} = r_{\rm thermal}/\sigma_{\rm thermal}$, where $\sigma_{\rm thermal}$ is the thermal neutron capture cross section. The results for the four samples are consistent within their uncertainties. The finally obtained averaged thermal neutron flux was $(2.2\pm0.4)\times10^5$ neutrons/cm^2. This result shows that the Cd differential method is useful for evaluation of thermal neutron flux and thermal neutron capture reaction cross section measurement in the LDNS experiment.

4. Conclusion
The LDNS is suitable for the study of nuclear astrophysics, because its neutrons have brightness, continuous energy distribution and extremely high flux in a single laser shot. The basic

techniques using LDNS have been developed. In near future, it is expected to obtain valuable results to contribute the understanding of the stellar nucleosynthesis and the effect of cosmic-ray neutron irradiation in the solar system.

References

[1] Mourou G and Tajima T 2011 *More Intense, Shorter Pulses Science* **331** 41
[2] Hayakawa T et al 2017 *Quan. Beam Sci.* **1** 3
[3] Barbui M et al 2013 *Phys. Rev. Lett.* **111** 082502
[4] Wang W 2023 *Phys. Lett.* B **843** 138034
[5] Norreys P A et al 1998 *Plasma Phys. Control. Fusion* **40** 175
[6] Disdier L et al 1999 *Phys. Rev. Lett.* **82** 1454
[7] Ditmire T et al 1999 *Nature* **398** 489
[8] Lancaster K L et al 2004 *Phys. Plasmas* **11** 3404
[9] Higginson D P et al 2011 *Phys. Plasmas* **18** 100703
[10] Youssef A et al 2005 *Phys. Plasmas* **12** 110703
[11] Mirfayzi S R et al 2020 *Appl. Phys. Lett.* **116** 174102
[12] Roth M et al 2013 *Phys. Rev. Lett.* **110** 1
[13] Kar S et al 2016 *New J. Phys.* **18** 53002
[14] Alejo A et al 2017 *Plasma Phys. Control. Fusion* **59** 064004
[15] Kleinschmidt A et al 2018 *Phys. Plasmas* **25** 53101
[16] Yogo A et al 2023 *Phys. Rev. X* **13** 011011
[17] Habs D et al 2011 *Applied Physics* B **103** 471
[18] Hill P Y and Wu Y 2021 *Phys. Rev.* C **103** 014602
[19] Berstein L et al 2014 *Plasma and Fusion Research* **9** 4404101
[20] Mirfayzi S R et al 2015 *Rev. Sci. Instrum.* **86** 073308
[21] Hayakawa T Shizuma T and Iizuka T 2023 *Comm. Phys.* **6** 299
[22] Beer H et al 1981 *Astrophys. J. Supp.* **46** 295
[23] Hayakawa T et al 2004 *Phys. Rev. Lett.* **93** 161102
[24] Patchett P J 1983 *Geochim. Cosmochim. Acta* **46** 81
[25] Bizzarro M et al 2003 *Nature* **421** 931
[26] Scherer E 2001 *Science* **293** 683
[27] Amelin Y 2005 *Science* **310** 839
[28] Iizuka T et al 2017 *Lithos* **274-275** 304
[29] Mori T et al 2021 *Phys. Rev.* C **104** 015808
[30] Sands Q G et al 2011 *Earth Planet. Sci. Lett.* **186** 335
[31] Sprung P et al 2010 *Earth Planet. Sci. Lett.* **295** 1
[32] Mori T et al 2022 *J. Phys. G Nucl. Part. Phys.* **49** 065103