Phys. Lett. B 852 (2024) 138622

Contents lists available at ScienceDirect

Physics Letters B

journal homepage: www.elsevier.com/locate/physletb

Letter

Vortex photon induced nuclear reaction: Mechanism, model, and application to the studies of giant resonance and astrophysical reaction rate

Yi Xu [a,*], Dimiter L. Balabanski [a,*], Virgil Baran [b,c], Cristian Iorga [b,d], Catalin Matei [a]

[a] Extreme Light Infrastructure - Nuclear Physics (ELI-NP), Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH), Strada Reactorului 30, Bucharest-Magurele, 077125, Ilfov, Romania

[b] Faculty of Physics, University of Bucharest, Strada Atomistilor 405, Bucharest-Magurele, 077125, Ilfov, Romania

[c] Academy of Romanian Scientists, Strada Ilfov 3, Sector 5, 050044, Bucharest, Romania

[d] National Institute for Laser, Plasma and Radiation Physics, Strada Atomistilor 409, Bucharest-Magurele, 077125, Ilfov, Romania

ARTICLE INFO

Editor: Baha Balantekin

Keywords:
Vortex photon
Reaction model
Giant resonance
Nuclear astrophysics

ABSTRACT

The vortex photon beam induced nuclear reaction is studied. The interaction formalism of nuclei with vortex photons is developed and incorporated into the statistical reaction model to calculate reaction cross-sections. For 138 nuclei of high nuclear astrophysics and structure interest, the cross-sections of γ-ray emission and neutron production from the decay of the giant resonances (GR) populated by vortex photons, *e.g.*, (γ^{vo},γ_{emit}) and (γ^{vo},n$_{prod.}$), are computed. It is shown that for the (γ^{vo},γ_{emit}) and (γ^{vo},n$_{prod.}$) cross-sections, the GR contribution of an individual L is either enhanced or suppressed depending on the parameters of vortex γ-rays, and the contribution from the GR of a specific L can be identified and deduced. To this end, a novel method to exclusively determine the γ-strength function (γSF) for the GR of a specific L is proposed considering the (γ^{vo},γ_{emit}) and (γ^{vo},$n_{prod.}$) measurements, and the feasibility studies demonstrate that the γSF for the giant quadrupole resonance can be extracted. Furthermore, the astrophysical reaction rates of the vortex photon induced reactions in p-process are investigated. It is indicated that photo-nuclear reactions induced by vortex photons will bring new insights in nuclear physics and astrophysics research.

1. Introduction

Since first discussed [1], orbital angular momentum (OAM) photons, also referred to as vortex or twisted photons, open new research avenues across several scientific fields (see Ref. [2–5] for recent reviews). On a quantum level, rare transitions in atoms and nanostructures resulting from new selection rules [6–9], time-resolved spectroscopy [10], and other atomic physics applications [11–15] were reported. Although it has been suggested that vortex photons can modify the photo-disintegration cross-section of the deuteron [16] or the photo-production of $\Delta(1232)$ baryons in nuclear targets [17], their application in nuclear physics research has not been studied in depth. Here, we demonstrate the perspectives for studies of giant resonances (GR) of higher multipolarity, $L \geq 2$.

The GRs constitute a general feature of nuclei and are understood as collective vibrational excitations. After the first observation of strong enhancement of the photo-absorption cross-section [18], the giant dipole resonance (GDR) was theoretically [19] and experimentally [20,21] studied. So far, different vibrational modes have been observed, characterized by various multipolarities and isospins depending on whether the protons and neutrons oscillate in-(isoscalar) or out-of-phase (isovector). A large number of measurements were dedicated to studying the giant quadrupole resonance (GQR) and giant octopole resonance (GOR). In particular, the isoscalar GQR was discovered in proton and electron inelastic scattering [22–24] and intensively studied with different experimental approaches [25–35,37,36,38–42], while the isovector GQR was exclusively detected in photon-induced measurements [43,44].

In order to quantitatively describe the GR, the γ-strength function (γSF) defining the probability of excitation and decay of the nucleus via γ-ray transitions, was considered [45–47]. The γSF is a fundamental nuclear property and plays a significant role in statistical model calculation [48], especially in the astrophysical energy range [49–55]. The reliable extraction of the γSF for the GR of higher multipolarity at lower energies is non-trivial due to its larger widths and speculative locations. Moreover, the GR of higher multipolarity usually overlaps

* Corresponding author.
E-mail addresses: yi.xu@eli-np.ro (Y. Xu), dimiter.balabanski@eli-np.ro (D.L. Balabanski).

https://doi.org/10.1016/j.physletb.2024.138622
Received 10 January 2024; Received in revised form 27 March 2024; Accepted 28 March 2024
Available online 3 April 2024

with the GDR, and in the detection of the statistical γ-ray [56–59] and particle [60–63] emissions, the GDR dominates. It is therefore understandable that in a discernible search for GR of higher multipolarity, separation or suppression of the GDR component is required.

On the other hand, possible astrophysical observations of vortex photons were discussed in Ref. [64]. In the outlook section of Ref. [65], the possible impact of vortex photons in nuclear astrophysics was outlined. However, detailed studies in this direction have not been done. It was theorized that vortex photons may be generated in extreme astrophysical environments [65–70], which would result in considerable changes of the photo-disintegration cross-sections. Therefore, it is interesting to investigate the impact of photo-nuclear reactions induced by vortex photons to the astrophysical processes.

The laser-Compton backscattering between an electron beam and a vortex laser pulse was proposed to generate the vortex γ-rays [71], and was considered to attain high photon energy while preserving the OAM of the incident laser photons [72,65,73–75]. An attempt to generate vortex γ-ray beams was carried out at the free-electron laser (FEL) facility, HIγS of Duke University, USA, where the vortex FEL photons were observed [76]. However, so far they were not used in physics experiments. The possibility of creating intense vortex γ-ray beams in laser-ion interactions was likewise discussed [77]. Recent studies with ultra-intense and ultrashort laser pulses demonstrated the generation of high-energy photon bursts via non-linear Compton scattering [78–81]. This only further spurned the interest to produce vortex photons at high-power laser facilities, where electrons are accelerated in laser-matter interaction [82,83]. While the generation of vortex photons were reported during such experiments [84,82,83,85,86], the intrinsic OAM carried by these photons is not well understood yet. Still, considering the intense research efforts undertaken, there is a cause for optimism that soon the vortex γ-ray beams will be available for photo-nuclear research.

In this letter, we report the novel studies of nuclear reaction induced by vortex γ-rays and its application to determine the GR of higher multipolarity, of which our preliminary results had been reported in a previous conference proceedings [87]. In particular, we develop the interaction formalism of nuclei with vortex photons, and apply it to the statistical reaction model calculation. For 138 nuclei of high nuclear astrophysics and structure interest, we compute the cross-sections of γ-ray emission and neutron production from the decay of the GR populated by vortex photons. Inspired by the calculations, we propose a novel approach to determine the γSF for the GR of a specific higher multipolarity considering the measurements with vortex γ-ray beams, and demonstrate that this method is particularly feasible and promising to determine the γSF for the GQR. Finally, we study the astrophysical rates of the vortex photon induced reactions in p-process.

2. Formalism of vortex photon beam

Vortex wave photons are generally described by a Bessel beam, whose vector potential $\vec{A}^{vo}$ is [71,12,2,16,14,17]

$$\vec{A}^{vo}_{\kappa,k_z,m_\gamma,\lambda}(\vec{r}) = \int \vec{A}^{pl}_{\vec{k},\lambda}(\vec{r})a_{m_\gamma\kappa}(\vec{k}_\perp)\frac{d^2\vec{k}_\perp}{(2\pi)^2} \tag{1}$$

with the amplitude $a_{m_\gamma\kappa}(\vec{k}_\perp) = (-i)^{m_\gamma} e^{im_\gamma\phi_k}\frac{2\pi}{\kappa}\delta(|\vec{k}_\perp| - \kappa)$. The integral of Eq. (1) indicates that the vortex photon beam is constructed by a superposition of standard plane wave photons, whose vector potential is $\vec{A}^{pl}_{\vec{k},\lambda}(\vec{r}) = \vec{e}_{\vec{k}\lambda}e^{i\vec{k}\cdot\vec{r}}$ with momentum $\vec{k}$ and helicity λ. The propagation direction of these plane wave photons is defined by the polar and azimuthal angles (θ_k and ϕ_k) of $\vec{k}$ with respect to the quantization z-axis, such that the momenta $\vec{k}$ of these plane wave components have identical θ_k in respect to the z-axis, but different ϕ_k in the $[0,2\pi]$ range. Thus, the wave vector $\vec{k}$ can be decomposed as $\vec{k} = \vec{k}_\perp + \vec{k}_z$ with the transverse momentum $\vec{k}_\perp$ and the longitudinal (along the quantization z-axis) momentum $\vec{k}_z$. Assuming the absolute values $|\vec{k}| = k$, $|\vec{k}_\perp| = \kappa$ and $|\vec{k}_z| = k_z$, one can obtain $k^2 = \kappa^2 + k_z^2$ with $\kappa = k\sin\theta_k$ and $k_z = k\cos\theta_k$. Here $\theta_k = \arctan(\kappa/k_z)$ characterizes the ratio of transverse to longitudinal momenta. In Eq. (1), m_γ is the projection of the total angular momentum (TAM) along the z-axis for the vortex photons.

For a nuclear excitation induced by a vortex photon, the interaction Hamiltonian is $\hat{H}^{vo}_{int} = -\frac{1}{c}\int \vec{j}\cdot\vec{A}^{vo}_{\kappa,k_z,m_\gamma,\lambda}(\vec{r})d^3\vec{r}$, where $\vec{j}$ is the nuclear current density. The transition amplitude can be represented in terms of the total angular momentum (J) and its projection (M) along the z-axis:

$$\begin{aligned}\langle J_f M_f|\hat{H}^{vo}_{int}|J_i M_i\rangle &= \frac{\sqrt{2\pi}}{c}e^{im_\gamma\phi_b}\sum_{L=1}^{\infty}\sum_{M=-L}^{L} i^{L-M}\sqrt{2L+1}\\ &\langle J_f M_f|[\hat{T}^{el}_{LM} + \lambda\hat{T}^{mag}_{LM}]|J_i M_i\rangle \mathcal{D}^L_{M\lambda}(\phi_b,\theta_k,0)J_{m_\gamma-M}(\kappa b).\end{aligned} \tag{2}$$

Here, L is the quantum number of orbital angular momentum (multipolarity), M is the magnetic quantum number with $M = [-L, -L+1, ..., L]$, $\hat{T}^{el}_L$ and $\hat{T}^{mag}_L$ [88] are the electric and magnetic multipole operators, respectively, ϕ_b is the azimuthal angle of the position of the nucleus in respect of the quantization z-axis considering the impact parameter b, $\mathcal{D}$ is the Wigner-D rotation matrix, and J is the Bessel function.

The total photo-absorption cross-section induced by vortex photons is then derived from the transition amplitude (Eq. (2)) and the photon flux [89,90,2]:

$$\sigma^{vo}_{abs} = \sum_{X=el}^{mag}\sum_{L=1}^{\infty}\frac{\sigma^{XL}}{\cos\theta_k}\frac{\sum\limits_{M=-L}^{L}|d^L_{M\lambda}(\theta_k)J_{m_\gamma-M}(\kappa b)|^2}{\sum\limits_{\sigma=-1}^{1}|d^1_{\sigma\lambda}(\theta_k)J_{m_\gamma-\sigma}(\kappa b)|^2}, \tag{3}$$

where d is the Wigner d-matrix. σ^{XL} represents the photo-absorption cross-section of the individual spherical multipole components. Eq. (3) indicates that the photo-absorption cross-section induced by vortex photons is factorized into a dynamic contribution given by individual electric or magnetic spherical multipole components and a corresponding geometric factor. Such geometric factor is determined by the parameters θ_k and m_γ of the vortex photons and the impact parameter b.

Note that the derivation of Eq. (3) is independent of any nuclear models, and it can be further adopted in a specific nuclear reaction model. Considering the single particle transition, σ^{XL} in Eq. (3) can be written as

$$\begin{aligned}\sigma^{XL} &= \frac{(8\pi^3)L+1}{L[(2L+1)!!]^2}(\frac{E_\gamma}{\hbar c})^{2L-1}B(XL)\rho_f(E_f)\\ &= (2L+1)(\pi\hbar c)^2E_\gamma^{2L-1}f_{XL}(E_\gamma),\end{aligned} \tag{4}$$

where E_γ is the vortex photon energy with $E_\gamma = E_f - E_i = \hbar ck$, E_i is the energy of the initial state, E_f is the final state energy, $B(XL)$ is the reduced transition probability which depends on the nuclear structure properties, $\rho_f(E_f)$ is the level density of the final state at E_f, and f_{XL} is the γSF. Note that $B(XL)$, $\rho_f(E_f)$ and f_{XL} are accessible experimentally or theoretically, which makes the calculation of the cross-section possible.

3. Reaction model

In order to further investigate the photo-nuclear cross-sections induced by vortex photons, the Hauser-Feshbach model [48] is considered in the present study. The Hauser-Feshbach model describes the compound reaction mechanism including two processes, *i.e.*, the absorption of vortex photon to form a compound nucleus by GR excitation, and its consequent decay. Here, the γ-ray emission and neutron production from the decay of the GR excited by vortex photons, *e.g.*, the $(\gamma^{vo},\gamma_{emit})$ and $(\gamma^{vo},n_{prod.})$ reaction channels, are further investigated. Combining Eq. (3) and the Hauser-Feshbach model, the cross-sections of $(\gamma^{vo},\gamma_{emit})$ and $(\gamma^{vo},n_{prod.})$ can be expressed as $\sigma^{vo}_{\gamma_{emit}} = \sigma^{vo}_{abs}\langle T_\gamma\rangle$ and $\sigma^{vo}_{n_{prod.}} = \sigma^{vo}_{abs}\langle T_n\rangle$, respectively, where the transmission coefficient $\langle T\rangle$ is usually calculated from the nuclear structure inputs including the γSF, the

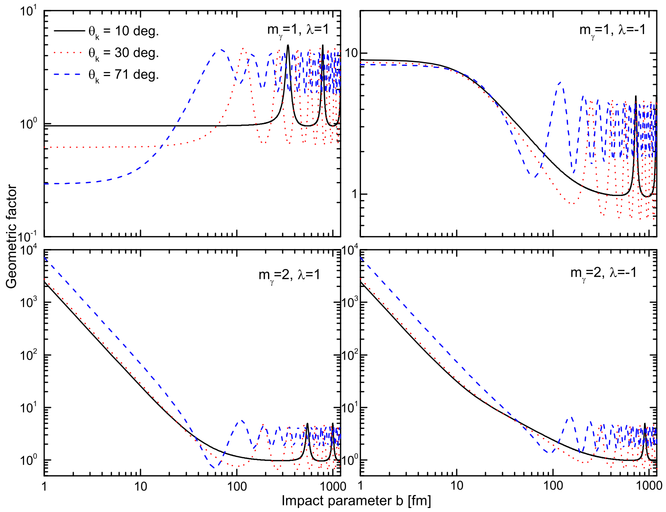

Fig. 1. The geometric factor for $L = 2$ (GQR) in Eq. (3) as a function of the impact parameter b.

optical model potential, and the nuclear level scheme [92,91]. It is indicated that within an ideal two-step compound reaction model, $\sigma^{vo}_{\gamma_{emit}}$ or $\sigma^{vo}_{n_{prod.}}$ is contributed from two parts, the formation cross-section σ^{vo}_{abs} of the compound nucleus and the decay possibility, represented by $\langle T\rangle$, of the compound nucleus. Compared with the formation cross-section $\sigma^{pl}_{abs} = \sum_{XL}\sigma^{XL}$ of the plane wave photon induced reaction, σ^{vo}_{abs} includes the specific electromagnetic multipole excitations characterized by the parameters of the vortex beam (see Eq. (3)). After the formation of compound nucleus takes place, the conventional statistical decay follows for both cases of plane wave and vortex beam. Note that these features may change when introducing multi-step reaction mechanism [92].

The model described above can be employed to compute the cross-sections of $(\gamma^{vo}, \gamma_{emit})$ and $(\gamma^{vo}, n_{prod.})$ with any parameters of the vortex photons. In the present study, we perform the calculations considering the parameters of $m_\gamma = 1$ and 2, and $\theta_k = 10$, 30, 71 deg. The three θ_k values are selected based on Refs. [12,14], in order to evidence the evolution of the cross-sections at small (10 deg.), intermediate (30 deg.) and large (71 deg.) pitch angles. Note that for a given electromagnetic transition, $\theta_k = 71$ deg. is the critical angle that changes the relative contributions from different magnetic quantum numbers to the cross-section [12].

The cross-section of the vortex photon induced reaction influenced by the impact parameter b is investigated. Eq. (3) reveals that the geometric factor determines the ratio of σ^{vo}_{abs} to σ^{pl}_{abs} for each electromagnetic multipole component. For $L = 1$, the geometric factor degenerates to $1/\cos\theta_k$ and is irrelevant to the impact parameter b. For $L = 2$ (the GQR component), the geometric factors are calculated with different impact parameter b, and the results are shown in Fig. 1 for the induced vortex photon energy of 8 MeV, a typical value for the photonuclear measurements. Note that the upper limit of $b = 1240$ fm is considered, corresponding to the wavelength of the photon with the energy of 1 MeV. It can be seen that, in the region below $b \approx 50$ fm where the photonuclear reaction takes place close to the axis of the vortex photon beam, the geometric factor is monotonic and indicates a clear and significant enhancement or suppression on the component of $L = 2$ in Eq. (3). On the other hand, in the region above $b \approx 50$ fm where the reaction occurs far away from the axis of the vortex photon beam, the geometric factor presents a periodic change, and different values of the impact parameter b could result in the same geometric factor leading to the same enhancement or suppression on the component of $L = 2$. Hence, the behaviors of the geometric factor in these two regions of the impact parameter b are distinctly different from each other. Considering that the enhancement or suppression of the electromagnetic multiple component can be explicitly illustrated in the calculation involving the impact parameter b below ≈ 50 fm, here $b = 10$ fm, which is the typical size of the nucleus, is used for the calculations.

Meanwhile, we restrict ourselves to merely consider the GDR and the GQR components, reflected by σ^{X1} and σ^{X2}, respectively. Combining Eq. (3) and the transmission coefficient $\langle T_{re}\rangle$ (here the subscript re represents γ_{emit} or $n_{prod.}$), the cross-sections $\sigma^{vo}_{\gamma_{emit}}$ and $\sigma^{vo}_{n_{prod.}}$ for $m_\gamma = 1$ can be given by

$$\sigma^{vo}_{re}(m_\gamma = 1) \approx \sum_{X=el}^{mag} \langle T_{re}\rangle \left[\frac{\sigma^{X1}}{\cos\theta_k} + \frac{\sigma^{X2}}{\cos\theta_k} \frac{|d^2_{1\lambda}(\theta_k)|^2}{|d^1_{1\lambda}(\theta_k)|^2} \right], \tag{5}$$

where the approximation $\kappa b \ll 1$ is used. Eq. (5) indicates that both the GDR and the GQR components contribute to the cross-section $\sigma^{vo}_{re}(m_\gamma = 1)$, and these contributions are scaled by the factors containing θ_k. Similarly, considering $m_\gamma = 2$ in Eq. (3), the cross-section $\sigma^{vo}_{re}(m_\gamma = 2)$ can be explicitly specified, too. Generally, Eqs. (3) and (5) indicate that for a given m_γ, the contribution from the GR of an individual multipolarity L to σ^{vo}_{re} can be either enhanced or suppressed for different θ_k.

Moreover, the difference between $\sigma^{vo}_{re}(m_\gamma = 2)$ and $\sigma^{vo}_{re}(m_\gamma = 1)$ is obtained, which is

$$\sigma^{vo}_{re}(m_\gamma = 2) - \sigma^{vo}_{re}(m_\gamma = 1) \approx \sum_{X=el}^{mag} \langle T_{re}\rangle \left[\frac{\sigma^{X2}}{\cos\theta_k} \left(\frac{|d^2_{2\lambda}(\theta_k)|^2 \frac{4}{(\kappa b)^2} - |d^2_{1\lambda}(\theta_k)|^2}{|d^1_{1\lambda}(\theta_k)|^2} \right) \right]. \tag{6}$$

Eq. (6) demonstrates that the GDR is eliminated and only the GQR contributes to this difference between $\sigma^{vo}_{re}(m_\gamma = 2)$ and $\sigma^{vo}_{re}(m_\gamma = 1)$. Generally, when calculating the difference between the cross-sections σ^{vo}_{re} of two given m_γ, the GR component of a specific multipolarity L in these σ^{vo}_{re} can be either eliminated or retained in the obtained difference. This feature presents opportunity to exclusively determine the γSF for the GR of the given multipolarity. In particular, in $\sigma^{vo}_{re}(m_\gamma = 2) - \sigma^{vo}_{re}(m_\gamma = 1)$, only the GQR contribution remains.

To further evaluate σ^{X1}, σ^{X2} and $\langle T_{re}\rangle$ in Eqs. (5) and (6), various nuclear structure ingredients are taken into account. The level schemes are constructed by combining the discrete experimental levels from the RIPL-3 library [93] plus the microscopic nuclear level density [94]. The microscopic optical model potentials [95,96] are used for computing $\langle T_n\rangle$. In order to calculate σ^{X1}, σ^{X2} and $\langle T_\gamma\rangle$, the γSF is needed. In general, the γSF can be derived from microscopic calculations [97–112] with the advanced treatment of nuclear deformation [113–118], or phenomenological methods [119–123]. In the present study, the γSF for the GDR and the GQR are obtained from the Hartree-Fock-Bogoliubov plus Quasiparticle Random Phase Approximation (HFB+QRPA) calculations [124]. Such HFB+QRPA model utilizes the Skyrme effective interaction derived from the accurate HFB mass model [125], and its reliability is demonstrated by the good agreement between the model calculations and the available experimental data [124]. Furthermore, it is illustrated that [124] for most nuclei, except the extreme neutron-rich species of which the measurements are not feasible, the HFB+QRPA γSF considered in the present study are quite close to the γSF derived from the full microscopic D1M-HFB+QRPA including the deformation effect.

4. Result

In the present calculation, 138 nuclei of high nuclear astrophysics and structure interest were selected [126–133,135,134,136–140,34,58,141–143,31,144–146,43]. The relevance and the corresponding references for these nuclei are provided in Appendix. For the $(\gamma^{vo}, \gamma_{emit})$ reaction on ^{90}Zr, ^{100}Mo, ^{120}Sn, and ^{208}Pb, Fig. 2 displays the calculated results of $\sigma^{vo}_{\gamma_{emit}}(m_\gamma = 1)$ and $\sigma^{vo}_{\gamma_{emit}}(m_\gamma = 2) - \sigma^{vo}_{\gamma_{emit}}(m_\gamma = 1)$ at θ_k

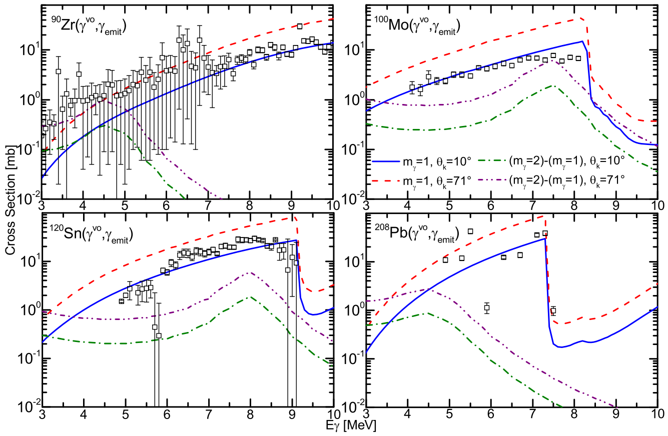

Fig. 2. The calculated cross-section $\sigma^{vo}_{\gamma_{emit}}(m_\gamma=1)$ (blue solid and red dashed lines) and the cross-section difference $\sigma^{vo}_{\gamma_{emit}}(m_\gamma=2)-\sigma^{vo}_{\gamma_{emit}}(m_\gamma=1)$ (green dash-dotted and purple dash-dot-dotted lines) for the $(\gamma^{vo},\gamma_{emit})$ reaction on ^{90}Zr, ^{100}Mo, ^{120}Sn, and ^{208}Pb at θ_k = 10 and 71 deg, respectively. The available γ-scattering data measured by normal photons are shown for comparison.

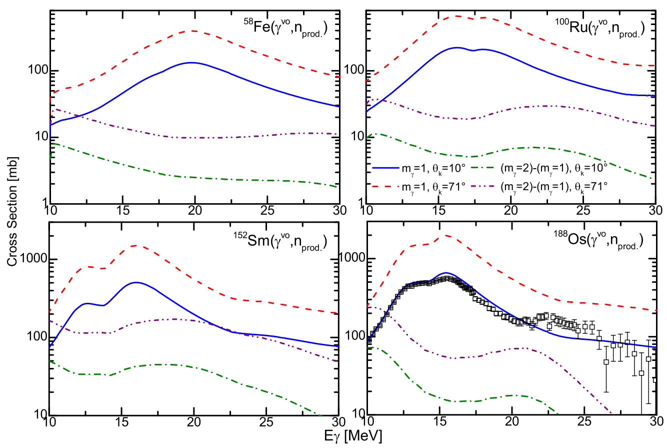

Fig. 3. The calculated cross-section $\sigma^{vo}_{n_{prod.}}(m_\gamma=1)$ (blue solid and red dashed lines) and the cross-section difference $\sigma^{vo}_{n_{prod.}}(m_\gamma=2)-\sigma^{vo}_{n_{prod.}}(m_\gamma=1)$ (green dashed-dotted and purple dashed-dotted-dotted lines) for the $(\gamma^{vo},n_{prod.})$ reaction on ^{58}Fe, ^{100}Ru, ^{152}Sm, and ^{188}Os at θ_k = 10 and 71 deg, respectively. The experimental data of ^{188}Os$(\gamma,n_{prod.})$ are shown for comparison.

= 10 and 71 deg, compared to the γ-scattering data measured by normal photons [136,137,147,146]. Eq. (5) indicates that the GDR and the GQR contributions to $\sigma^{vo}_{\gamma_{emit}}(m_\gamma=1)$ are modified by $1/cos\theta_k$ and $\frac{|d^2_{1\lambda}(\theta_k)|^2}{cos\theta_k|d^1_{1\lambda}(\theta_k)|^2}$, respectively. In particular, these two factors are 1.015 and 0.955 in the case of θ_k = 10 deg, respectively. This means that both of the GDR and the GQR contributions to $\sigma^{vo}_{\gamma_{emit}}(m_\gamma=1)$ are hardly changed. Therefore, the calculated results of $\sigma^{vo}_{\gamma_{emit}}(m_\gamma=1)$ at θ_k = 10 deg fairly reproduce the experimental data, as shown in Fig. 2. In the case of θ_k = 71 deg, the dominant GDR component in $\sigma^{vo}_{\gamma_{emit}}(m_\gamma=1)$ is enhanced by a factor of 3.072. For the results of $\sigma^{vo}_{\gamma_{emit}}(m_\gamma=2)-\sigma^{vo}_{\gamma_{emit}}(m_\gamma=1)$, Eq. (6) reveals that the GDR contribution is eliminated, and the GQR component is enhanced by a factor involving θ_k and κb. Such enhancement of the GQR component is significant especially at lower energies, which is reflected by the comparable values between $\sigma^{vo}_{\gamma_{emit}}(m_\gamma=2)-\sigma^{vo}_{\gamma_{emit}}(m_\gamma=1)$ and $\sigma^{vo}_{\gamma_{emit}}(m_\gamma=1)$ shown in Fig. 2.

For the $(\gamma^{vo},n_{prod.})$ reaction on the targets of ^{58}Fe, ^{100}Ru, ^{152}Sm, and ^{188}Os, Fig. 3 displays the calculated results of $\sigma^{vo}_{n_{prod.}}(m_\gamma=1)$ and $\sigma^{vo}_{n_{prod.}}(m_\gamma=2)-\sigma^{vo}_{n_{prod.}}(m_\gamma=1)$ at θ_k = 10 and 71 deg, compared to the experimental data only available for ^{188}Os [148]. Similar conclusions as for the $(\gamma^{vo},\gamma_{emit})$ reaction can be drawn for the $(\gamma^{vo},n_{prod.})$ reaction, too.

Eq. (6) and the calculated results shed light on a novel approach to determine the γSF for the GR of higher multipolarity L. In particular, measurements of the $(\gamma^{vo},\gamma_{emit})$ and $(\gamma^{vo},n_{prod.})$ cross-sections respectively using the vortex γ-ray beams with m_γ = 1 and m_γ = 2 are suggested. Taking into account the measured cross-sections $\sigma^{vo}_{\gamma_{emit}}(m_\gamma=1)$, $\sigma^{vo}_{\gamma_{emit}}(m_\gamma=2)$, $\sigma^{vo}_{n_{prod.}}(m_\gamma=1)$, and $\sigma^{vo}_{n_{prod.}}(m_\gamma=2)$, the photo-absorption cross-sections σ^{X1} and σ^{X2} can be deduced by Eqs. (5)-(6), and accordingly, the γSF f_{X1} and f_{X2} can be determined from Eq. (4). Furthermore, it is worth mentioning that the cross-sections $\sigma^{vo}_{\gamma_{emit}}$ and $\sigma^{vo}_{n_{prod.}}$ can be measured for any values of m_γ by configuring the parameters of vortex γ-rays. Considering the measured $\sigma^{vo}_{\gamma_{emit}}(m_\gamma)$, $\sigma^{vo}_{n_{prod.}}(m_\gamma)$, $\sigma^{vo}_{\gamma_{emit}}(m_\gamma-1)$ and $\sigma^{vo}_{n_{prod.}}(m_\gamma-1)$, the γSF for the GR of the specific multipolarity $L = m_\gamma$ can be determined.

In order to demonstrate the feasibility of the proposed approach, an (N,Z) plot of the ratios of $\sigma^{vo}_{\gamma_{emit}}(m_\gamma=2)-\sigma^{vo}_{\gamma_{emit}}(m_\gamma=1)$ to $\sigma^{vo}_{\gamma_{emit}}(m_\gamma=1)$ for the 138 nuclei are presented in Fig. 4 at E_γ = 6 MeV and θ_k = 30 deg. The results show that for about 20% of the studied nuclei, the ratio is larger than one, which indicates that the enhanced GQR component in $\sigma^{vo}_{\gamma_{emit}}(m_\gamma=2)-\sigma^{vo}_{\gamma_{emit}}(m_\gamma=1)$ is larger than the dominant GDR contribution to $\sigma^{vo}_{\gamma_{emit}}(m_\gamma=1)$. Similarly, an (N,Z) plot of the ratios of $\sigma^{vo}_{n_{prod.}}(m_\gamma=2)-\sigma^{vo}_{n_{prod.}}(m_\gamma=1)$ to $\sigma^{vo}_{n_{prod.}}(m_\gamma=1)$ for the same 138 nuclei are presented in Fig. 5 at E_γ = 26 MeV and θ_k = 30 deg. The results show that for 17 heavier nuclei with the mass number A > 120, the ratio is larger than one.

Furthermore, the experimental yield Y of the emitted γ-ray is estimated for ^{208}Pb$(\gamma^{vo},\gamma_{emit})$ at E_γ = 6 MeV and θ_k = 30 deg using $Y = d\times\rho\times\epsilon\times t\times\int_E n_\gamma(E)\sigma^{vo}_{\gamma_{emit}}(E)dE$. For m_γ = 1 and 2, $Y(m_\gamma=1)$ = 1910 and $Y(m_\gamma=2)$ = 1970 count-per-day are obtained, respectively. Here, a vortex γ-ray beam with a spectral density n_γ of $5\cdot10^3$ photons/(s·eV), a target thickness d of 0.1 mm, and a detector efficiency ϵ of 0.1% are used in the estimation, combining the calculated cross-sections of ^{208}Pb$(\gamma^{vo},\gamma_{emit})$. This demonstrates that for ^{208}Pb, the extraction of the γSF for the GQR at lower energies is feasible experimentally.

The astrophysical p-process is an important way of nucleosynthesis to produce some stable and proton-rich nuclei beyond iron, via the photodisintegration channels of $(\gamma$,n), $(\gamma$,p), and (γ,α) [149–168]. The p-process occurs in massive star evolution and stellar explosive site in which a strong magnetic field may exist. Recent studies [69,70] demonstrated that the vortex photon can be generated via synchrotron radiations in the strong magnetic field associated with astrophysical objects. Therefore, such generated vortex photon can be involved in the photodisintegration for the p-process nucleosynthesis. In this situation, the astrophysical reaction rates of the vortex photon induced reaction shall be taken into account, which are expected to impact the stellar abundance. To this end, it is necessary to first obtain the photodisintegration reaction rate induced by vortex photons. In astrophysical objects, the collision between the vortex photon and the nucleus occurs randomly, and thus the parameters (the pitch angle θ_k and the impact parameter b) characterizing the photonuclear interaction may vary. Hence, the determination of the vortex photon induced reaction rate depends on the specific values of the parameters θ_k and b.

In the present study, the astrophysical reaction rates of the vortex photon induced reactions are calculated considering various values of θ_k and b. In particular, the average result of the vortex photon induced reaction rates computed by each value of $b \le 1240$ fm, $N_A<\sigma\upsilon>^{vo}_{\bar{b}}$, are obtained. Furthermore, $N_A<\sigma\upsilon>^{vo}_{\bar{b}}$ is compared with the plane wave photon induced reaction rate $N_A<\sigma\upsilon>^{pl}$, and the ratios of $N_A<\sigma\upsilon>^{vo}_{\bar{b}}$ to $N_A<\sigma\upsilon>^{pl}$ are shown in Fig. 6 for the ^{96}Ru$(\gamma$,p), ^{132}Ba$(\gamma$,n) and ^{148}Gd(γ,α) reactions. Here, θ_k = 45 deg is considered in the calculation of $N_A<\sigma\upsilon>^{vo}_{\bar{b}}$. Fig. 6 illustrates that at the lower

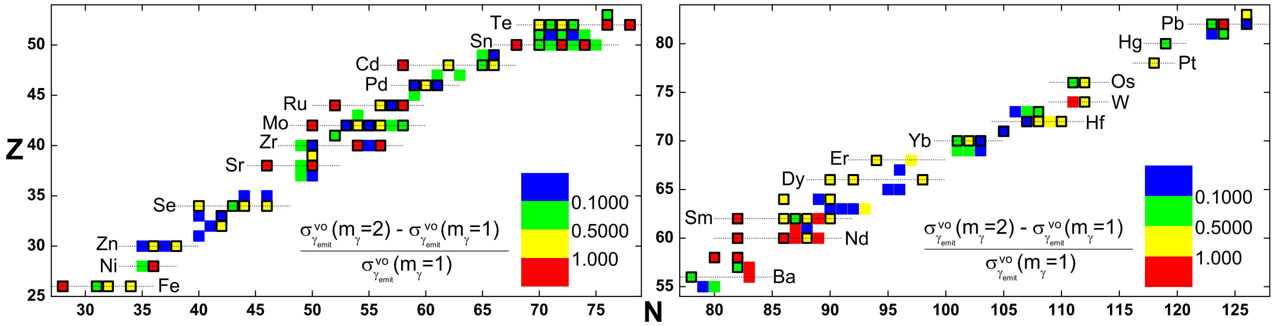

Fig. 4. An (N, Z) plot of the ratios of $\sigma^{vo}_{\gamma_{emit}}(m_\gamma = 2) - \sigma^{vo}_{\gamma_{emit}}(m_\gamma = 1)$ to $\sigma^{vo}_{\gamma_{emit}}(m_\gamma = 1)$ for the 138 nuclei at $E_\gamma = 6$ MeV and $\theta_k = 30$ deg. The stable nuclei are marked in black edging.

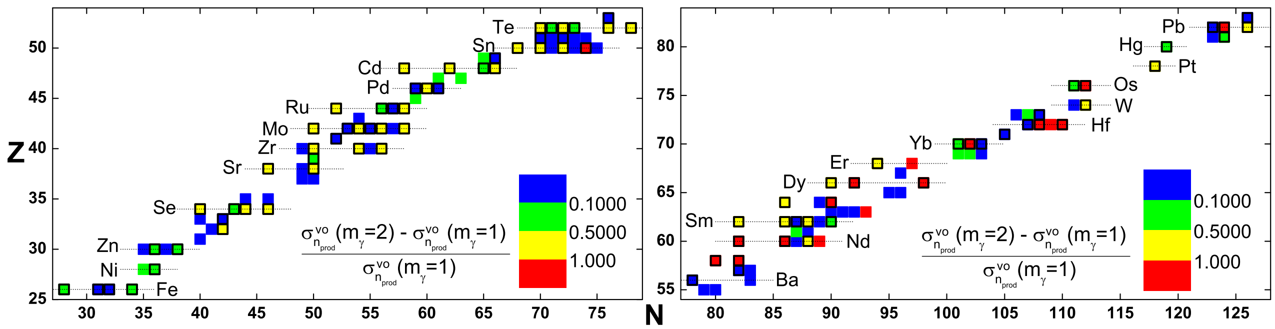

Fig. 5. An (N, Z) plot of the ratios of $\sigma^{vo}_{n_{prod.}}(m_\gamma = 2) - \sigma^{vo}_{n_{prod.}}(m_\gamma = 1)$ to $\sigma^{vo}_{n_{prod.}}(m_\gamma = 1)$ for the 138 nuclei at $E_\gamma = 26$ MeV and $\theta_k = 30$ deg. The stable nuclei are marked in black edging.

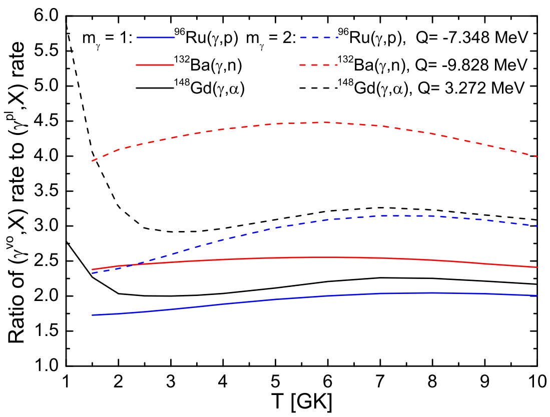

Fig. 6. The ratios of the vortex photon induced reaction rates ($N_A < \sigma v >^{vo}_{b}$) to the plane wave photon induced reaction rates ($N_A < \sigma v >^{pl}$) for the ^{96}Ru(γ,p), ^{132}Ba(γ,n) and ^{148}Gd(γ,α) reactions. $N_A < \sigma v >^{vo}_{b}$ is the average result of the vortex photon induced reaction rates computed by each value of $b \leq 1240$ fm. $\theta_k = 45$ deg is considered in the calculation of $N_A < \sigma v >^{vo}_{b}$.

temperature (T < 2 GK), the reaction rate of the exoergic reaction (Q > 0) ^{148}Gd(γ, α) is significantly enhanced for the vortex photon induced reaction. This is because the most effective energy range of the exoergic reaction (similar to the Gamow window of the charged particles induced reaction) that contributes to the reaction rate at a given temperature is much lower than that of the endoergic reaction (Q < 0), and in such lower energy range the GQR contribution to the photonuclear cross-section and the reaction rate can be significantly enhanced for the vortex photon induced reaction. In the temperature range of the astrophysical p-process (2 − 3 GK), Fig. 6 demonstrates that $N_A < \sigma v >^{vo}_{b}$ are generally larger than $N_A < \sigma v >^{pl}$ by a factor of 2 − 4. Therefore, to include the vortex photon induced reaction rates in the nucleosynthesis at the proper astrophysical site needs to be considered.

5. Summary and outlook

In summary, we carry out the novel study of nuclear reaction induced by vortex γ-rays to investigate GR of higher multipolarity, $L \geq 2$. The interaction formalism of nuclei with vortex photons is developed. Combining this formalism and the Hauser-Feshbach model, the cross-sections of $(\gamma^{vo}, \gamma_{emit})$ and $(\gamma^{vo}, n_{prod.})$ for 138 nuclei of high nuclear astrophysics and structure interest are computed with different parameters m_γ and θ_k of the vortex γ-rays. The results indicate that for a given m_γ, the contribution from the GR of an individual multipolarity L to the calculated cross-section is either enhanced or suppressed for different θ_k. Furthermore, when computing the difference between the cross-sections of two m_γ, the GR component of a specific multipolarity L can be either eliminated or retained in the obtained difference. Thus, a novel approach to exclusively determine the γSF for the GR of a specific multipolarity L is suggested. In particular, measurements of the cross-sections of the γ-ray emission and neutron production channels with different parameters of the vortex γ-ray beams are proposed, and it is demonstrated that the enhanced GR of a specific multipolarity L can be identified and deduced from the experimental results. The explicit calculations indicate that it is feasible to extract the γSF for the GQR, especially at lower energies. In general, information related to the γSF for the GR of higher multipolarity is missing, and experiments using vortex γ-ray beams could fill in this niche.

The availability of vortex γ-ray beams will open plenty of opportunities for photo-nuclear research. One could also selectively populate high-spin nuclear isomers by exciting high-lying doorway states, or directly populate the levels with spin $I > 1$ and study selectively their decay. Needless to say, this opens the avenue for new types of nuclear γ-ray spectroscopic studies at low energies. In the present study, we have considered a large class of nuclei of astrophysics interest, since possible sites for the generation of vortex photons are different extreme stel-

Table A.1
List of the 138 nuclei selected for the present study.

Nuclei	Relevance	Reference
^{73}As, ^{75}As, ^{74}Se, ^{84}Sr, ^{92}Mo, ^{96}Ru, ^{106}Cd	X(γ,p) reaction for p-nuclei abundances, with the selected nuclei X	Table II in [126]
^{80}Se, ^{79}Br, ^{89}Y, ^{93}Nb, ^{96}Mo, ^{97}Tc, ^{106}Pd, ^{110}Cd, ^{118}Sn, ^{134}Ba, ^{138}Ce, ^{150}Gd, ^{156}Dy, ^{158}Dy, ^{162}Er	Branchings of γ-process	Table III in [127]
^{60}Fe, ^{64}Ni, ^{65}Zn, ^{77}Se, ^{87}Sr, ^{88}Sr, ^{97}Mo, ^{105}Pd, ^{148}Pm, ^{152}Sm, ^{153}Eu, ^{155}Eu, ^{156}Eu, ^{154}Gd, ^{165}Er, ^{171}Tm, ^{172}Tm, ^{180}Ta, ^{181}Ta, ^{187}Os, ^{188}Os, ^{199}Hg, ^{205}Tl, ^{205}Pb, ^{206}Pb	(n,γ)X reaction for s-process, with the selected nuclei X	Section 5 in [128]
^{98}Mo, ^{99}Mo, ^{146}Nd, ^{147}Nd, ^{148}Nd, ^{149}Nd, ^{148}Sm, ^{149}Sm, ^{150}Sm, ^{171}Yb, ^{172}Yb, ^{173}Yb, ^{179}Hf, ^{180}Hf, ^{181}Hf, ^{186}W	(n,γ)X reaction for s-process, with the selected nuclei X	[129]
^{122}Sn, ^{123}Sn, ^{125}Sn, ^{121}Sb, ^{123}Sb, ^{124}Sb, ^{125}Sb, ^{122}Te, ^{123}Te, ^{125}Te	(n,γ)X reaction for s-only isotopes in s-process, with the selected nuclei X	[130]
^{57}Fe, ^{58}Fe, ^{66}Zn, ^{67}Zn, ^{68}Zn, ^{71}Ga, ^{73}Ge, ^{74}Ge, ^{78}Se, ^{81}Br, ^{86}Rb, ^{87}Rb, ^{94}Zr, ^{95}Mo, ^{100}Ru, ^{101}Ru, ^{102}Ru, ^{104}Rh, ^{107}Pd, ^{108}Ag, ^{110}Ag, ^{114}In, ^{120}Sn, ^{122}Sb, ^{124}Te, ^{129}I, ^{134}Cs, ^{140}La, ^{139}Ba	(n,γ)X reaction for s-process, with the selected nuclei X	Tables IV and VII in [131]
^{63}Ni, ^{95}Zr, ^{96}Zr, ^{135}Cs, ^{149}Pm, ^{151}Sm, ^{154}Eu, ^{153}Gd, ^{160}Tb, ^{161}Tb, ^{163}Ho, ^{170}Tm, ^{179}Ta, ^{185}W, ^{204}Tl	(n,γ)X reaction for s-process branching point, with the selected nuclei X	[132]
^{113}Cd, ^{121}Sn, ^{176}Lu, ^{182}Hf	nuclei (isomer) structure for studies of s- and r- processes	Section 3 in [133]
^{89}Zr	Surprisingly large ^{88}Zr(n,γ) cross-section was measured. Photo-nuclear study of ^{89}Zr with vortex γ-rays is proposed.	[134]
^{54}Fe, ^{90}Zr, ^{100}Mo, ^{114}Cd, ^{115}In, ^{124}Sn, ^{128}Te, ^{130}Te, ^{139}La, ^{140}Ce, ^{142}Nd, ^{144}Sm, ^{164}Dy, ^{196}Pt, ^{208}Pb, ^{209}Bi	Experiments with plane wave photons were performed for the selected nuclei. Measurements using vortex γ-rays are suggested.	[135–140,34,58,141–143, 31,144–146,43]

lar environments. It is worth studying this problem in detail, because the interaction between nuclei and vortex photons will influence the photo-disintegration cross-sections, and in turn, will change the overall picture of star evolution modeling.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The authors are grateful to the anonymous reviewer for the helpful comments. The authors thank Dr. Vlad Vasilca for reading and revising the manuscript. This work was carried out under the contract PN 23.21.01.06 sponsored by the Romanian Ministry of Research, Innovation and Digitalization, the contract No. ELI_15/16.10.2020 supported by ELI-RO project funded by the Institute of Atomic Physics (Magurele, Romania), and Extreme Light Infrastructure - Nuclear Physics (ELI-NP) Phase II, the project co-financed by the Romanian Government and the European Regional Development Fund - the Competitiveness Operational Programme (1/07.07.2016, COP, ID 1334). This work was supported by a grant of the Romanian Ministry of Research, Innovation and Digitization, CNCS - UEFIS- CDI, project number PN-III-P4-PCE-2021-1014, PN-III-P4-PCE-2021-0595, and PN-III-P1-1.1-TE2021-1464 within PNCDI III.

Appendix A. Selection of the 138 nuclei of nuclear astrophysics and structure interest

In Appendix, 138 nuclei of nuclear astrophysics and structure interest are listed in Table A.1.

References

[1] L. Allen, M.W. Beijersbergen, R.J.C. Spreeuw, J.P. Woerdman, Phys. Rev. A 45 (1992) 8185.
[2] B.A. Kzyazev, V. Serbo, Phys. Usp. 61 (2018) 449.
[3] Y. Shen, X. Wang, Z. Xie, C. Min, X. Fu, Q. Liu, M. Gong, X. Yuan, Light: Sci. Appl. 9 (2019) 90.
[4] G.F. Quinteiro Rosen, P.I. Tamborenea, T. Kuhn, Rev. Mod. Phys. 94 (2022) 035003.
[5] I.P. Ivanov, Prog. Part. Nucl. Phys. 127 (2022) 103987.
[6] A. Picon, J. Mompart, J.R. Vazquez de Aldana, et al., Opt. Express 18 (2010) 3660.
[7] C.T. Schmiegelow, J. Schulz, H. Kaufmann, T. Ruster, U.G. Poschinger, F. Schmidt-Kaler, Nat. Commun. 7 (2016) 12998.
[8] A. Afanasev, C.E. Carlson, C.T. Schmiegelow, J. Schulz, F. Schmidt-Kaler, M. Solyanik, New J. Phys. 20 (2018) 023032.
[9] S. Reich, N.S. Mueller, M. Bubula, ACS Photonics 7 (2020) 1537.
[10] M.A. Noyan, J.M. Kikkawa, Appl. Phys. Lett. 107 (2015) 032406.
[11] A. Afanasev, C.E. Carlson, A. Mukherjee, Phys. Rev. A 88 (2013) 033841.
[12] H.M. Scholz-Marggraf, S. Fritzsche, V. Serbo, A. Afanasev, A. Surzhykov, Phys. Rev. A 90 (2014) 013425.
[13] A. Surzhykov, D. Seipt, V. Serbo, S. Fritzsche, Phys. Rev. A 91 (2015) 013403.
[14] S.A.-L. Schulz, S. Fritzsche, R.A. Müller, A. Surzhykov, Phys. Rev. A 100 (2019) 043416.
[15] A.A. Peshkov, Y.M. Bidasyuk, R. Lange, N. Huntemann, E. Peik, A. Surzhykov, Phys. Rev. A 107 (2023) 023106.
[16] A. Afanasev, V.G. Serbo, M. Solyanik, J. Phys. G, Nucl. Part. Phys. 45 (2018) 055102.
[17] A. Afanasev, C.E. Carlson, Ann. Phys. (Berlin) 534 (2022) 2100228.
[18] W. Bothe, W. Gentner, Z. Phys. 106 (1937) 236–248.
[19] A.B. Migdal, J. Phys. (USSR) 8 (1944) 331.
[20] G.C. Baldwin, G.S. Klaiber, Phys. Rev. 73 (1947) 1156.
[21] G.C. Baldwin, G.S. Klaiber, Phys. Rev. 71 (1948) 3.
[22] A. Pitthan, Th. Walcher, Phys. Lett. B 36 (1971) 563.
[23] M.B. Lewis, F. Bertrand, Nucl. Phys. A 196 (1972) 337.
[24] S. Fukuda, Y. Torizuka, Phys. Rev. Lett. 29 (1972) 1109.

[25] P. Axel, K.K. Min, D.C. Sutton, Phys. Rev. C 2 (1970) 689.
[26] B.L. Herman, D.D. Paul, R.A. Alvarez, P. Meyer, D.L. Olson, Phys. Rev. C 19 (1979) 1205.
[27] A.M. Nathan, P.L. Cole, P.T. Debevec, S.D. Hoblit, S.F. LeBrun, D.H. Wright, Phys. Rev. C 34 (1986) 480.
[28] N. Pietralla, D. Belic, P. von Brentano, C. Fransen, R.-D. Herzberg, U. Kneissl, H. Maser, P. Matschinsky, A. Nord, T. Otsuka, H.H. Pitz, V. Werner, I. Wiedenhöver, Phys. Rev. C 58 (1998) 796.
[29] D. Belic, C. Arlandini, J. Besserer, J. de Boer, J.J. Carroll, J. Enders, T. Hartmann, F. Käppeler, H. Kaiser, U. Kneissl, M. Loewe, H.J. Maier, H. Maser, P. Mohr, P. von Neumann-Cosel, A. Nord, H.H. Pitz, A. Richter, M. Schumann, S. Volz, A. Zilges, Phys. Rev. Lett. 83 (1999) 5242.
[30] G. Rusev, R. Schwengner, F. Dönau, M. Erhard, S. Frauendorf, E. Grosse, A.R. Junghans, L. Käubler, K. Kosev, L.K. Kostov, S. Mallion, K.D. Schilling, A. Wagner, H. von Garrel, U. Kneissl, C. Kohstall, M. Kreutz, H.H. Pitz, M. Scheck, F. Stedile, P. von Brentano, C. Fransen, J. Jolie, A. Linnemann, N. Pietralla, V. Werner, Phys. Rev. C 73 (2006) 044308.
[31] C. Nair, A.R. Junghans, M. Erhard, D. Bemmerer, R. Beyer, E. Grosse, K. Kosev, M. Marta, G. Rusev, K.D. Schilling, R. Schwengner, A. Wagner, Phys. Rev. C 81 (2010) 055806.
[32] V. Derya, N. Tsoneva, T. Aumann, M. Bhike, J. Endres, M. Gooden, A. Hennig, J. Isaak, H. Lenske, B. Löher, N. Pietralla, D. Savran, W. Tornow, V. Werner, A. Zilges, Phys. Rev. C 93 (2016) 034311.
[33] T. Beck, J. Beller, N. Pietralla, M. Bhike, J. Birkhan, V. Derya, U. Gayer, A. Hennig, J. Isaak, B. Löher, V.Yu. Ponomarev, A. Richter, C. Romig, D. Savran, M. Scheck, W. Tornow, V. Werner, A. Zilges, M. Zweidinger, Phys. Rev. Lett. 118 (2017) 212502.
[34] J. Isaak, D. Savran, B. Löher, T. Beck, M. Bhike, U. Gayer Krishichayan, N. Pietralla, M. Scheck, W. Tornow, V. Werner, A. Zilges, M. Zweidinger, Phys. Lett. B 788 (2019) 225.
[35] D. Savran, J. Isaak, R. Schwengner, R. Massarczyk, M. Scheck, W. Tornow, G. Battaglia, T. Beck, S.W. Finch, C. Fransen, U. Friman-Gayer, R. Gonzalez, E. Hoemann, R.V.F. Janssens, S.R. Johnson, M.D. Jones, J. Kleemann Krishichayan, D.R. Little, D. O'Donnell, O. Papst, N. Pietralla, J. Sinclair, V. Werner, O. Wieland, J. Wilhelmy, Phys. Rev. C 106 (2022) 044324.
[36] F.E. Bertrand, Annu. Rev. Nucl. Sci. 26 (1976) 457.
[37] A. van der Woude, Prog. Part. Nucl. Phys. 18 (1987) 217.
[38] R. Pitthan, F.R. Buskirk, J.N. Dyer, E.F. Hunter, G. Pozinsky, Phys. Rev. C 19 (1979) 299.
[39] T. Ichihara, M. Ishihara, H. Ohnuma, T. Niizeki, Y. Satou, H. Okamura, S. Kubono, M.H. Tanaka, Y. Fuchi, Phys. Rev. Lett. 89 (2002) 142501.
[40] M. Itoh, H. Sakaguchi, M. Uchida, T. Ishikawa, T. Kawabata, T. Murakami, H. Takeda, T. Taki, S. Terashima, N. Tsukahara, Y. Yasuda, M. Yosoi, U. Garg, M. Hedden, B. Kharraja, M. Koss, B.K. Nayak, S. Zhu, H. Fujimura, M. Fujiwara, K. Hara, H.P. Yoshida, H. Akimune, M.N. Harakeh, M. Volkerts, Phys. Rev. C 68 (2003) 064602.
[41] X. Chen, Y.W. Lui, H.L. Clark, Y. Tokimoto, D.H. Youngblood, Phys. Rev. C 80 (2009) 014312.
[42] Y.K. Gupta, U. Garg, J. Hoffman, J. Matta, P.V. Madhusudhana Rao, D. Patel, T. Peach, K. Yoshida, M. Itoh, M. Fujiwara, K. Hara, H. Hashimoto, K. Nakanishi, M. Yosoi, H. Sakaguchi, S. Terashima, S. Kishi, T. Murakami, M. Uchida, Y. Yasuda, H. Akimune, T. Kawabata, M.N. Harakeh, Phys. Rev. C 93 (2016) 044324.
[43] S.S. Henshaw, M.W. Ahmed, G. Feldman, A.M. Nathan, H.R. Weller, Phys. Rev. Lett. 107 (2011) 222501.
[44] G. Colo, U. Garg, H. Sagawa, Eur. Phys. J. A 50 (2014) 26.
[45] A. Bohr, B.R. Mottelson, Nuclear Structure, Volume II Nuclear Deformations, Addison-Wesley/W. A. Benjamin, Inc., United States, 1975.
[46] J. Speth, A. van der Woude, Rep. Prog. Phys. 44 (1981) 720.
[47] K. Goeke, J. Speth, Annu. Rev. Nucl. Part. Sci. 32 (1982) 65.
[48] W. Hauser, H. Feshbach, Phys. Rev. 87 (1952) 366.
[49] G. Michaud, W.A. Fowler, Astrophys. J. 173 (1972) 157.
[50] M. Arnould, Astron. Astrophys. 19 (1972) 92.
[51] T. Rauscher, F.-K. Thielemann, K.-L. Kratz, Phys. Rev. C 56 (1997) 1613.
[52] S. Goriely, S. Hilaire, A.J. Koning, Astron. Astrophys. 487 (2008) 767.
[53] Y. Xu, S. Goriely, A. Jorissen, G.L. Chen, M. Arnould, Astron. Astrophys. 549 (2013) A106.
[54] M. Beard, E. Uberseder, R. Crowter, M. Wiescher, Phys. Rev. C 90 (2014) 034619.
[55] N. Tsoneva, S. Goriely, H. Lenske, R. Schwengner, Phys. Rev. C 91 (2015) 044318.
[56] R. Schwengner, G. Rusev, N. Benouaret, R. Beyer, M. Erhard, E. Grosse, A.R. Junghans, J. Klug, K. Kosev, L. Kostov, C. Nair, N. Nankov, K.D. Schilling, A. Wagner, Phys. Rev. C 76 (2007) 034321.
[57] A.P. Tonchev, S.L. Hammond, J.H. Kelley, E. Kwan, H. Lenske, G. Rusev, W. Tornow, N. Tsoneva, Phys. Rev. Lett. 104 (2010) 072501.
[58] J. Isaak, D. Savran, M. Krticka, M.W. Ahmed, J. Beller, E. Fiori, J. Glorius, J.H. Kelley, B. Löher, N. Pietralla, C. Romig, G. Rusev, M. Scheck, L. Schnorrenberger, J. Silva, K. Sonnabend, A.P. Tonchev, W. Tornow, H.R. Weller, M. Zweidinger, Phys. Lett. B 727 (2013) 361.
[59] A. Makinaga, R. Massarczyk, M. Beard, R. Schwengner, H. Otsu, T. Al-Abdullah, M. Anders, D. Bemmerer, R. Hannaske, R. John, A.R. Junghans, S.E. Müller, M. Röder, K. Schmidt, A. Wagner, Phys. Rev. C 94 (2016) 044304.
[60] P. Mohr, T. Shizuma, H. Ueda, S. Goko, A. Makinaga, K.Y. Hara, T. Hayakawa, Y.-W. Lui, H. Ohgaki, H. Utsunomiya, Phys. Rev. C 69 (2004) 032801(R).
[61] H. Utsunomiya, A. Makinaga, S. Goko, T. Kaihori, H. Akimune, T. Yamagata, M. Ohta, H. Toyokawa, S. Müller, Y.-W. Lui, S. Goriely, Phys. Rev. C 74 (2006) 025806.
[62] H. Utsunomiya, S. Goriely, H. Akimune, H. Harada, F. Kitatani, S. Goko, H. Toyokawa, K. Yamada, T. Kondo, O. Itoh, M. Kamata, T. Yamagata, Y.-W. Lui, I. Daoutidis, D.P. Arteaga, S. Hilaire, A.J. Koning, Phys. Rev. C 82 (2010) 064610.
[63] H. Utsunomiya, T. Renstrøm, G.M. Tveten, S. Goriely, T. Ari-izumi, D. Filipescu, J. Kaur, Y.-W. Lui, W. Luo, S. Miyamoto, A.C. Larsen, S. Hilaire, S. Péru, A.J. Koning, Phys. Rev. C 99 (2019) 024609.
[64] M. Harwit, Astrophys. J. 597 (2003) 1266.
[65] Y. Taira, T. Hayakawa, M. Katoh, Sci. Rep. 7 (2017) 1.
[66] Y. Taira, M. Katoh, Astrophys. J. 860 (2018) 45.
[67] T. Maruyama, T. Hayakawa, T. Kajino, Sci. Rep. 9 (2019) 51.
[68] T. Maruyama, T. Hayakawa, T. Kajino, Sci. Rep. 9 (2019) 7998.
[69] T. Maruyama, T. Hayakawa, T. Kajino, M.-K. Cheoun, Phys. Lett. B 826 (2022) 136779.
[70] T. Maruyama, T. Hayakawa, R. Hajima, T. Kajino, M.-K. Cheoun, Phys. Rev. Res. 5 (2023) 043289.
[71] U.D. Jentschura, V.G. Serbo, Phys. Rev. Lett. 106 (2011) 013001.
[72] V. Petrillo, G. Dattoli, I. Drebot, F. Nguyen, Phys. Rev. Lett. 117 (2016) 123903.
[73] M. Katoh, M. Fujimoto, H. Kawaguchi, K. Tsuchiya, K. Ohmi, T. Kaneyasu, Y. Taira, M. Hosaka, A. Mochihashi, Y. Takashima, Phys. Rev. Lett. 118 (2017) 094801.
[74] Y.-Y. Chen, K.Z. Hatsagortsyan, C.H. Keitel, Matter Radiat. Extrem. 4 (2019) 024401.
[75] O.V. Bogdanov, P. Kazinski, G.Y. Lazarenko, Phys. Rev. D 99 (2019) 116016.
[76] P. Liu, J. Yan, A. Afanasev, S.V. Benson, H. Hao, S.F. Mikhailov, V.G. Popov, Y.K. Wu, arXiv:2007.15723 [physics.acc-ph], 2020.
[77] V.G. Serbo, A. Surzhykov, A. Volotka, Ann. Phys. (Berlin) 534 (2021) 2100199.
[78] S. Chen, N.D. Powers, I. Ghebregziabher, C.M. Maharjan, C. Liu, G. Golovin, S. Banerjee, J. Zhang, N. Cunningham, A. Moorti, S. Clarke, S. Pozzi, D.P. Umstadter, Phys. Rev. Lett. 110 (2013) 155003.
[79] G. Sarri, D.J. Corvan, W. Schumaker, J.M. Cole, A. Di Piazza, H. Ahmed, C. Harvey, C.H. Keitel, K. Krushelnick, S.P.D. Mangles, Z. Najmudin, D. Symes, A.G.R. Thomas, M. Yeung, Z. Zhao, M. Zepf, Phys. Rev. Lett. 113 (2014) 224801.
[80] J.M. Cole, K.T. Behm, E. Gerstmayr, T.G. Blackburn, J.C. Wood, C.D. Baird, M.J. Duff, C. Harvey, A. Ilderton, A.S. Joglekar, K. Krushelnick, S. Kuschel, M. Marklund, P. McKenna, C.D. Murphy, K. Poder, C.P. Ridgers, G.M. Samarin, G. Sarri, D.R. Symes, A.G.R. Thomas, J. Warwick, M. Zepf, Z. Najmudin, S.P.D. Mangles, Phys. Rev. X 8 (2018) 011020.
[81] K. Poder, M. Tamburini, G. Sarri, A. Di Piazza, S. Kuschel, C.D. Baird, K. Behm, S. Bohlen, J.M. Cole, D.J. Corvan, M. Duff, E. Gerstmayr, C.H. Keitel, K. Krushelnick, S.P.D. Mangles, P. McKenna, C.D. Murphy, Z. Najmudin, C.P. Ridgers, G.M. Samarin, D.R. Symes, A.G.R. Thomas, J. Warwick, M. Zepf, Phys. Rev. X 8 (2018) 031004.
[82] Y.Y. Liu, Y.I. Salamin, Z. Dou, Z. Xu, J. Li, Opt. Lett. 45 (2020) 395.
[83] J. Wang, X.B. Li, L.F. Gan, Y. Xie, C.L. Zhong, C.T. Zhou, S.P. Zhu, X.T. He, B. Qiao, Phys. Rev. Appl. 14 (2020) 014094.
[84] Z. Gong, R.H. Hu, H.Y. Lu, J.Q. Yu, D.H. Wang, E.G. Fu, C.E. Chen, X.T. He, X.Q. Yan, Plasma Phys. Control. Fusion 60 (2018) 044004.
[85] Y.T. Hu, J. Zhao, H. Zhang, Y. Lu, W.Q. Wang, L.X. Hu, F.Q. Shao, T.P. Yu, Appl. Phys. Lett. 118 (2021) 054101.
[86] M.A. Bake, T. Suo, X. Baisong, Plasma Sci. Technol. 24 (2022) 095001.
[87] Dimiter L. Balabanski, in: 13th International Spring Seminar on Nuclear Physics Perspectives and Challenges in Nuclear Structure after 70 Years of Shell Model (ISS 2022), 14/05/2022 - 20/05/2022, Sant'Angelo, Italy, Inst. Phys. Conf. Ser. 2453 (2023) 012030.
[88] T. deForest Jr., J.D. Walecka, Adv. Phys. 15 (1966) 1.
[89] K.Y. Bliokh, M.A. Alonso, E.A. Ostrovskaya, A. Aiello, Phys. Rev. A 82 (2010) 063825.
[90] A. Afanasev, C.E. Carlson, A. Mukherjee, J. Opt. 18 (2016) 074013.
[91] H.Y. Lan, Y. Xu, W. Luo, D.L. Balabanski, S. Goriely, M. La Cognata, C. Matei, A. Anzalone, S. Chesnevskaya, G.L. Guardo, D. Lattuada, R.G. Pizzone, S. Romano, C. Spitaleri, A. Taffara, A. Tumino, Z.C. Zhu, Phys. Rev. C 98 (2018) 054601.
[92] A.J. Koning, S. Hilaire, S. Goriely, Eur. Phys. J. A 59 (2023) 131.
[93] R. Capote, M. Herman, P. Obložinský, P.G. Young, S. Goriely, T. Belgya, A.V. Ignatyuk, A.J. Koning, S. Hilaire, V.A. Plujko, M. Avrigeanu, O. Bersillon, M.B. Chadwick, T. Fukahori, Z.G. Ge, Y.L. Han, S. Kailas, J. Kopecky, V.M. Maslov, G. Reffo, M. Sin, E.Sh. Soukhovitskii, P. Talou, Nucl. Data Sheets 110 (2009) 3107.
[94] S. Goriely, S. Hilaire, A.J. Koning, Phys. Rev. C 78 (2008) 064307.
[95] E. Bauge, J.P. Delaroche, M. Girod, Phys. Rev. C 63 (2001) 024607.
[96] Y. Xu, S. Goriely, A.J. Koning, S. Hilaire, Phys. Rev. C 90 (2014) 024604.
[97] E. Khan, N.V. Giai, Phys. Lett. B 472 (2000) 253.
[98] G. Colò, P. Bortignon, Nucl. Phys. A 696 (2001) 427.
[99] E. Khan, N. Sandulescu, N.V. Giai, M. Grasso, Phys. Rev. C 66 (2002) 024309.
[100] M. Bender, F.-H. Heenen, P.-G. Reinhard, Rev. Mod. Phys. 75 (2003) 121.
[101] N. Paar, P. Ring, T. Nikšiĉ, D. Vretenar, Phys. Rev. C 67 (2003) 034312.
[102] S. Goriely, E. Khan, M. Samyn, Nucl. Phys. A 739 (2004) 331.
[103] K. Hagino, N.V. Giai, H. Sagawa, Nucl. Phys. A 731 (2004) 264.
[104] N. Paar, D. Vretenar, E. Khan, G. Colò, Rep. Prog. Phys. 70 (2007) R02.
[105] P. Avogadro, T. Nakatsukasa, Phys. Rev. C 84 (2011) 014314.

[106] G. Scamps, D. Lacroix, Phys. Rev. C 88 (2013) 044310.
[107] E. Litvinova, P. Ring, V. Tselyaev, Phys. Rev. C 88 (2013) 044320.
[108] X. Roca-Maza, M. Brenna, B.K. Agrawal, P.F. Bortignon, G. Colò, Li-Gang Cao, N. Paar, D. Vretenar, Phys. Rev. C 87 (2013) 034301.
[109] S. Ebata, M. Kimura, Phys. Rev. C 91 (2015) 014309.
[110] M. Martini, S. Péru, S. Hilaire, S. Goriely, F. Lechaftois, Phys. Rev. C 94 (2016) 014304.
[111] D. Gambacurta, M. Grasso, O. Vasseur, Phys. Lett. B 777 (2018) 163.
[112] E. Yüksel, G. Colò, E. Khan, Y.F. Niu, Phys. Rev. C 97 (2018) 064308.
[113] V.O. Nesterenko, W. Kleinig, J. Kvasil, P. Vesely, P.-G. Reinhard, D.S. Dolci, Phys. Rev. C 74 (2006) 064306.
[114] J. Kvasil, V.O. Nesterenko, W. Kleinig, P.-G. Reinhard, P. Vesely, Phys. Rev. C 84 (2011) 034303.
[115] A. Repko, P.-G. Reinhard, V.O. Nesterenko, J. Kvasil, Phys. Rev. C 87 (2013) 024305.
[116] V.O. Nesterenko, V.G. Kartavenko, W. Kleinig, J. Kvasil, A. Repko, R.V. Jolos, P.-G. Reinhard, Phys. Rev. C 93 (2016) 034301.
[117] A. Repko, J. Kvasil, V.O. Nesterenko, P.-G. Reinhard, Eur. Phys. J. A 53 (2017) 221.
[118] V.O. Nesterenko, A. Repko, J. Kvasil, P.-G. Reinhard, Phys. Rev. Lett. 120 (2018) 182501.
[119] D.M. Brink, Nucl. Phys. 4 (1957) 215.
[120] P. Axel, Phys. Rev. 126 (1962) 671.
[121] W.V. Prestwich, M.A. Islam, T.J. Kennett, Z. Phys. A 315 (1984) 103.
[122] J. Kopecky, M. Uhl, Phys. Rev. C 41 (1990) 1941.
[123] S. Goriely, V. Plujko, Phys. Rev. C 99 (2019) 014303.
[124] Y. Xu, S. Goriely, E. Khan, Phys. Rev. C 104 (2021) 044301.
[125] S. Goriely, N. Chamel, J.M. Pearson, Phys. Rev. C 88 (2013) 061302(R).
[126] W. Rapp, J. Görres, M. Wiescher, H. Schatz, F. Käppeler, Astrophys. J. 653 (2006) 474.
[127] T. Rauscher, Phys. Rev. C 73 (2006) 015804.
[128] M. Wiescher, F. Käppeler, K. Langanke, Annu. Rev. Astron. Astrophys. 50 (2012) 165.
[129] S. Bisterzo, R. Gallino, F. Käppeler, M. Wiescher, G. Imbriani, O. Straniero, S. Cristallo, J. Görres, R.J. deBoer, Mon. Not. R. Astron. Soc. 449 (2015) 506.
[130] K. Takahashi, K. Blaum, Yu. Novikov, Astrophys. J. 819 (2016) 118.
[131] N. Nishimura, R. Hirschi, T. Rauscher, A.St.J. Murphy, G. Cescutti, Mon. Not. R. Astron. Soc. 469 (2017) 1752.
[132] C. Guerrero, C. Domingo-Pardo, F. Käppeler, J. Lerendegui-Marco, F.R. Palomo, J.M. Quesada, R. Reifarth, Eur. Phys. J. A 53 (2017) 87.
[133] G.W. Misch, S.K. Ghorui, P. Banerjee, Y. Sun, M.R. Mumpower, Astrophys. J. Suppl. Ser. 252 (2021) 2.
[134] J.A. Shusterman, N.D. Scielzo, K.J. Thomas, E.B. Norman, S.E. Lapi, C.S. Loveless, N.J. Peters, J.D. Robertson, D.A. Shaughnessy, A.P. Tonchev, Nature 565 (2019) 328.
[135] R. Schwengner, R. Massarczyk, R. Beyer, M. Bhike, B.A. Brown Krishichayan, K. Sieja, W. Tornow, D. Bemmerer, M. Butterling, V. Derya, M. Dietz, F. Fiedler, U. Friman-Gayer, A. Frotscher, M. Grieger, A. Hartmann, A.R. Junghans, T. Kögler, F. Ludwig, B. Lutz, H. Pai, T. Szücs, M.P. Takács, A. Wagner, Phys. Rev. C 101 (2020) 064303.
[136] R. Schwengner, G. Rusev, N. Tsoneva, N. Benouaret, R. Beyer, M. Erhard, E. Grosse, A.R. Junghans, J. Klug, K. Kosev, H. Lenske, C. Nair, K.D. Schilling, A. Wagner, Phys. Rev. C 78 (2008) 064314.
[137] G. Rusev, R. Schwengner, R. Beyer, M. Erhard, E. Grosse, A.R. Junghans, K. Kosev, C. Nair, K.D. Schilling, A. Wagner, F. Dönau, S. Frauendorf, Phys. Rev. C 79 (2009) 061302(R).
[138] R. Massarczyk, G. Schramm, T. Belgya, R. Schwengner, R. Beyer, D. Bemmerer, Z. Elekes, E. Grosse, R. Hannaske, A.R. Junghans, Z. Kis, T. Kögler, C. Lorenz, K. Schmidt, L. Szentmiklósi, A. Wagner, J.L. Weil, Phys. Rev. C 93 (2016) 014301.
[139] M. Versteegen, D. Denis-Petit, V. Méot, T. Bonnet, M. Comet, F. Gobet, F. Hannachi, M. Tarisien, P. Morel, M. Martini, S. Péru, Phys. Rev. C 94 (2016) 044325.
[140] M. Spieker, N. Tsoneva, V. Derya, J. Endres, D. Savran, M.N. Harakeh, S. Harissopulos, R.-D. Herzberg, A. Lagoyannis, H. Lenske, N. Pietralla, L. Popescu, M. Scheck, F. Schlüter, K. Sonnabend, V.I. Stoica, H.J. Wörtche, A. Zilges, Phys. Lett. B 752 (2016) 102.
[141] A. Makinaga, R. Schwengner, G. Rusev, F. Dönau, S. Frauendorf, D. Bemmerer, R. Beyer, P. Crespo, M. Erhard, A.R. Junghans, J. Klug, K. Kosev, C. Nair, K.D. Schilling, A. Wagner, Phys. Rev. C 82 (2010) 024314.
[142] B. Löher, D. Savran, T. Aumann, J. Beller, M. Bhike, N. Cooper, V. Derya, M. Duchêne, J. Endres, A. Hennig, P. Humby, J. Isaak, J.H. Kelley, M. Knörzer, N. Pietralla, V.Yu. Ponomarev, C. Romig, M. Scheck, H. Scheit, J. Silva, A.P. Tonchev, W. Tornow, F. Wamers, H. Weller, V. Werner, A. Zilges, Phys. Lett. B 756 (2016) 72.
[143] C.T. Angell, S.L. Hammond, H.J. Karwowski, J.H. Kelley, M. Krtička, E. Kwan, A. Makinaga, G. Rusev, Phys. Rev. C 86 (2012) 051302(R).
[144] O. Papst, V. Werner, J. Isaak, N. Pietralla, T. Beck, C. Bernards, M. Bhike, N. Cooper, B.P. Crider, U. Friman-Gayer, J. Kleemann Krishichayan, B. Löher, F. Naqvi, E.E. Peters, F.M. Prados-Estévez, R.S. Ilieva, T.J. Ross, D. Savran, W. Tornow, J.R. Vanhoy, Phys. Rev. C 102 (2020) 034323.
[145] R. Massarczyk, G. Schramm, A.R. Junghans, R. Schwengner, M. Anders, T. Belgya, R. Beyer, E. Birgersson, A. Ferrari, E. Grosse, R. Hannaske, Z. Kis, T. Kögler, K. Kosev, M. Marta, L. Szentmiklósi, A. Wagner, J.L. Weil, Phys. Rev. C 87 (2013) 044306.
[146] R. Schwengner, R. Massarczyk, B.A. Brown, R. Beyer, F. Dönau, M. Erhard, E. Grosse, A.R. Junghans, K. Kosev, C. Nair, G. Rusev, K.D. Schilling, A. Wagner, Phys. Rev. C 81 (2010) 054315.
[147] M. Müscher, J. Wilhelmy, R. Massarczyk, R. Schwengner, M. Grieger, J. Isaak, A.R. Junghans, T. Kögler, F. Ludwig, D. Savran, D. Symochko, M.P. Takács, M. Tamkas, A. Wagner, A. Zilges, Phys. Rev. C 102 (2020) 014317.
[148] B.L. Berman, D.D. Faul, R.A. Alvarez, P. Meyer, D.L. Olson, Phys. Rev. C 19 (1979) 1205.
[149] M. Arnould, C. Brihaye, Astron. Astrophys. 1 (1969) 193.
[150] S. Woosley, W. Howard, Astrophys. J. Suppl. Ser. 36 (1978) 285.
[151] K. Nomoto, F.-K. Thielemann, K. Yokoi, Astrophys. J. 286 (1984) 644.
[152] M. Rayet, M. Arnould, N. Prantzos, Astron. Astrophys. 227 (1990) 271.
[153] S. Fujimoto, M. Hashimoto, O. Koike, K. Arai, R. Matsuba, Astrophys. J. 585 (2003) 418.
[154] M. Arnould, S. Goriely, Phys. Rep. 384 (2003) 1.
[155] T. Hayakawa, N. Iwamoto, T. Shizuma, T. Kajino, H. Umeda, K. Nomoto, Phys. Rev. Lett. 93 (2004) 161102.
[156] T. Hayakawa, N. Iwamoto, T. Kajino, T. Shizuma, H. Umeda, K. Nomoto, Astrophys. J. 648 (2006) L47.
[157] W. Rapp, J. Görres, M. Wiescher, H. Schatz, F. Käppeler, Astrophys. J. 653 (2006) 474.
[158] S. Fujimoto, M. Hashimoto, K. Kotake, S. Yamada, Astrophys. J. 656 (2007) 382.
[159] T. Hayakawa, N. Iwamoto, T. Kajino, T. Shizuma, H. Umeda, K. Nomoto, Astrophys. J. 685 (2008) 1089.
[160] M. Kusakabe, N. Iwamoto, K. Nomoto, Astrophys. J. 726 (2011) 25.
[161] S. Wanajo, H.T. Janka, S. Kubono, Astrophys. J. 729 (2011) 46.
[162] C. Travaglio, F.K. Röpke, R. Gallino, W. Hillebrandt, Astrophys. J. 739 (2011) 93.
[163] T. Hayakawa, K. Nakamura, T. Kajino, S. Chiba, N. Iwamoto, M.K. Cheoun, G.J. Mathews, Astrophys. J. Lett. 779 (2013) L9.
[164] T. Rauscher, N. Dauphas, I. Dillmann, C. Fröhlich, Z. Fülöp, G. Gyürky, Rep. Prog. Phys. 76 (2013) 066201.
[165] N. Nishimura, T. Rauscher, R. Hirschi, A.S.J. Murphy, G. Cescutti, C. Travaglio, Mon. Not. R. Astron. Soc. 474 (2017) 3133.
[166] C. Travaglio, T. Rauscher, A. Heger, M. Pignatari, C. West, Astrophys. J. 854 (2018) 18.
[167] A. Choplin, S. Goriely, R. Hirschi, N. Tominaga, Astron. Astrophys. 661 (2022) A86.
[168] H. Sasaki, Y. Yamazaki, T. Kajino, M. Kusakabe, T. Hayakawa, M.-K. Cheoun, H. Ko, G.J. Mathews, Astrophys. J. 924 (2022) 29.