Photoneutron Reactions in Nuclear Astrophysics

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Abstract. Highly-monochromatic γ-ray beams are produced at the NewSUBARU synchrotron radiation facility by the inverse Compton scattering of laser photons from relativistic electrons. The latest s-process study in nuclear astrophysics with the γ-ray beam is presented.

1. Laser Compton scattering - photon accelerator at NewSUBARU

Highly-monochromatic γ-ray beams are produced at the synchrotron radiation facility NewSUBARU in the inverse Compton scattering of laser photons from relativistic electrons circulating in a storage ring [1].

The laser inverse Compton scattering plays a role of accelerating the mass-less particle, photon. The energy of scattered photons is expressed by

\[ E'_{\gamma} = \frac{4\gamma^2\epsilon_L}{1 + (\gamma\theta)^2 + 4\gamma\epsilon_L/(mc^2)}, \]

where \( \epsilon_L \) is the energy of a laser photon, \( mc^2 \) is the rest mass energy of an electron, \( \theta \) is the scattering angle of a laser photon with respect to the electron incident direction, and \( \gamma \) is the Lorentz factor for electron, \( \gamma = E_e/mc^2 \), defined by the total electron energy \( E_e \) and the rest mass energy. The energy amplification factor in nearly head-on collisions (\( \theta = 0 \)), \( E'_{\gamma}/\epsilon_L = 4\gamma^2 \), is very large on the order of \( 10^6 \) - \( 10^7 \) for several hundred MeV to a few GeV electrons so that an eV laser beam can...
be converted to an MeV \( \gamma \)-ray beam in the laser inverse Compton scattering. At NewSUBARU, one can produce low-energy \( \gamma \)-ray beams at a few MeV using a CO\(_2\) laser (wave length \( \lambda = 10.59 \, \mu \text{m} \)) and high-energy \( \gamma \)-ray beams at a few tens of MeV using a Nd:YVO\(_4\) laser (\( \lambda = 1064 \text{nm} \)) in collisions with 0.5 - 1.5 GeV electrons. Recently, the electron beam energy of the NewSUBARU storage ring was calibrated with the accuracy of the order of 10\(^{-5}\) by using the low-energy laser Compton scattered (LCS) \( \gamma \)-ray beam produced with a grating-fixed CO\(_2\) laser oscillated at a single line of the strongest master transition P(20) \([2]\). The central wave length of the P(20) transition is known (\( \lambda = 10.5915 \, \mu \text{m} \pm 3 \, \text{Å} \)) \([3]\) with the band width 1.3 Å in the full width at half maximum FWHM \([4]\). Including the band width, the accuracy of the wave length of CO\(_2\) laser is 4.1 \times 10^{-5}. A coaxial HPGe detector (64 mm in diameter \( \times \) 60 mm in length), which was calibrated with the standard \( \gamma \)-ray sources, \( ^{60}\)Co including the sum peak, \( ^{133}\)Ba, \( ^{137}\)Cs, and \( ^{152}\)Eu and a natural radioactivity \( ^{40}\)K, was used to measure the low energy LCS \( \gamma \) rays.

The full energy peaks of the measured \( \gamma \)-ray spectra were reproduced with the Monte Carlo code EGS4/PRESTA \([5]\), where the end-point energy of the full energy peak is sensitive to the electron beam energy. Figure 1 shows the result of the calibration, the difference of the calibrated energy \( E^e_\gamma \) from the nominal energy \( E^n_\gamma \), \( \Delta E = E^e_\gamma - E^n_\gamma \) as a function of \( E^n_\gamma \). The absolute energy calibration of the electron beams offers a standard for the energy calibration of high-energy LCS \( \gamma \)-ray beams produced with a Nd:YVO\(_4\) laser.

![Figure 1. The difference of the calibrated energy \( E^e_\gamma \) from the nominal energy \( E^n_\gamma \), \( \Delta E = E^e_\gamma - E^n_\gamma \) at the NewSUBARU storage ring.](image)

Figure 2 shows typical spectra of the high-energy LCS \( \gamma \)-ray beams recorded with a 3.5" \( \times \) 4.0" \( \text{LaBr}_3 \):Ce detector (solid lines) along with the GEANT4 simulations of the detector response function (dotted lines) and the incident \( \gamma \)-ray beam (gray lines). The experimental response functions are excellently reproduced by the GEANT4 simulation. Energy spreads of 1.2%, 1.4% and 1.6% in FWHM were obtained for the three incident \( \gamma \)-ray beams of 6.5, 10.0 and 13.0 MeV maximum energy, respectively.

2. s-process
Nuclear astrophysics links the microscopic system of the atomic nucleus with large galactic processes. Among many unknowns related to the synthesis of elements, a great challenge is to determine the radiative neutron capture cross section for unstable nuclei. In particular, radioactive nuclei along the line of \( \beta \) stability in the medium- to heavy-mass region has gained increasing interest. The cross sections are important to determine the s-process path at branching points where neutron capture and \( \beta \)
decay compete [6]. Although experimental data of radiative neutron capture cross sections for stable nuclei are well documented [7, 8], those for radioactive nuclei are scarce due to the difficulty of direct measurements that requires both an intense neutron beam and radioactive samples. While some of radioactive nuclei with half-lives \(T_{1/2}\) of the order of years have become objectives for direct measurements at the European Organization of Nuclear Research, the Los Alamos Neutron Science Center, and the Japan Proton Accelerator Research Complex, those with \(T_{1/2}\) of the order of days and shorter are far beyond the experimental scope at present.

The well-established \(\gamma\)-ray strength function (\(\gamma\)SF) method can be used for constraining the \((n, \gamma)\) cross sections for radioactive nuclei [9, 10]. Relying on the Brink hypothesis [11] linking the photodeexcitation process to photoabsorption, the method determines the \(\gamma\)SF, which commonly quantifies radiative neutron capture and photoneutron cross sections. Photoneutron cross sections provide a stringent experimental constraint in absolute scale on the \(\gamma\)SF around \(S_n\). When auxiliary \((\gamma, \gamma')\) and particle-\(\gamma\) coincidence data that help to construct the \(\gamma\)SF below \(S_n\) are unavailable, the method requires a systematic measurement of photoneutron cross sections for neighboring stable isotopes of a radioactive nucleus of interest, in addition to the existing \((n, \gamma)\) data which serve as experimental constraints on the \(\gamma\)SF below \(S_n\). Thus, a unified understanding of \((n, \gamma)\) and \((\gamma, n)\) cross sections throughout an isotopic chain offers a detailed information on the \(\gamma\)SF for a given nucleus formed by neutron capture on the radioactive nucleus. Such a systematic approach with the \(\gamma\)SF method was applied to zirconium [12], tin [13] and molybdenum [14] isotopes.

Very recently, the \(\gamma\)SF method has been applied to the neodymium [15] and samarium [16] isotope chains. Figure 3 shows photoneutron cross sections for neodymium isotopes in comparison with the Saclay data [17]. While a good agreement is obtained in the \(^{146,148}\text{Nd}\) cases, significant discrepancies are observed for the light Nd isotopes. Our experiment leads to cross section lowered by typically 20%. Such an overestimate by the Saclay photodata was also reported in previous comparisons for \(^{142}\text{Nd}\) with a renormalization by 0.86 [18], for \(^{144}\text{Sm}\) by 0.80 [19], and for \(^{89}\text{Rb}, \(^{88}\text{Sr}, \(^{89}\text{Y}, \(^{90}\text{Zr}, \(^{93}\text{Nb}, \(^{127}\text{I}, \(^{197}\text{Au}, \text{and } \(^{208}\text{Pb}\) by a factor 0.80—0.93 [20].

Our new photoneutron cross sections are compared to theoretical calculations obtained with the TALYS nuclear reaction code [21, 22] and two different models of the \(\gamma\)SF, namely the Skyrme HFB plus QRPA model [23] based on the BSk7 interaction, and the axially-symmetric-deformed Gogny HFB plus QRPA model based on the D1M interaction [24, 25, 26, 27]. As seen in Fig. 3, cross sections around the neutron threshold are better described by the D1M+QRPA model, although some deviations can be seen.

![Figure 2](image-url)

**Figure 2.** Typical spectra of the \(\gamma\)-ray beams recorded with a LaBr\(_3\):Ce detector (solid lines), the simulations of the response function (dotted lines) and of the incident \(\gamma\)-ray beam (gray lines).
We now turn to the reverse radiative neutron capture channel. It should be kept in mind that the corresponding cross section for incident keV neutrons depends sensitively on the $\gamma$SF, but in a rather lower energy range below the neutron threshold, typically around 6 MeV of $\gamma$-ray energy. The predicted tail of the $\gamma$SF at low energies therefore plays a fundamental role. On the basis of the Gogny HFB plus QRPA $\gamma$-ray strength [24], the reverse radiative neutron capture cross sections are now estimated with the TALYS reaction code [21, 22] for the stable and experimentally known $^{142,146,148}$Nd isotopes and compared with experimental cross sections in Fig. 4. In addition to the E1 strength function, the cross section calculation also depends on the adopted nuclear level density. We have used here the temperature-dependent HFB plus combinatorial model [28] normalized to the experimental s-wave spacing $D_0$ values [29].

As can be seen in Fig. 4, the TALYS calculation agrees well with experimental data for all the 6 Nd isotopes, which shows that within the uncertainties affecting the experimental $\gamma$SF and $D_0$ value, all $\gamma$SF data are compatible with both the photoabsorption above the threshold and the radiative capture channels below the threshold.

The $\gamma$SF method can now be applied to the experimentally unknown cross section $^{147}$Nd(n, $\gamma$)$^{148}$Nd making use of the same nuclear inputs. In the case of $^{148}$Nd, experimental information exists on the resonance spacing at the neutron binding energy, namely $D_0 = 4.0 \pm 1.5$ eV [29]. The 40% error on $D_0$ corresponds to the major uncertainty still affecting the prediction of the $^{147}$Nd(n, $\gamma$)$^{148}$Nd cross section, giving rise to a range of predicted cross section within a typically 20–30%, as shown in Fig. 5. The American ENDF/B-VII.1 evaluations [41] is seen to be in relatively good agreement with our estimate, but the Russian ROSFOND-2010 evaluation gives rather lower cross sections above typically a few keVs and the Japanese JENDL-4.0 evaluation larger values above typically 100 keV.
The resulting Maxwellian-averaged cross section of astrophysical interest amounts, at 30 keV, to 880 ± 170 mb. Our Maxwellian-averaged cross section (and consequently, also the ENDF/B-VII.1 and JENDL-4.0 ones) is found to be significantly larger than the value of 544 ± 90 mb recommended in Ref. [7] as well as all the theoretical values compiled in the KADONIS library [8] ranging between 387 and 663 mb.

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Figure 4. Comparison between the measured radiative neutron capture cross sections [30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40] with TALYS calculations making use of the D1M+QRPA E1 strength.

Figure 5. Prediction of the 147Nd(n,γ)148Nd cross section. The dotted, dashed, and dash-dot curves correspond to the Japanese JENDL-4.0, American ENDF/B-VII.1, and Russian ROSFOND-2010 evaluations [41].

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