Photodisintegration of $^{80}$Se as a probe of neutron capture for the s-process branch-point nucleus $^{79}$Se

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Photoneutron cross sections were measured for $^{80}$Se near the neutron separation energy with the laser Compton scattering $\gamma$ rays. The stellar neutron capture rate for $^{79}$Se was evaluated by using the photodisintegration data as constraints on the E1 $\gamma$ strength function within the framework of the Hauser-Feshbach statistical model. The result is compared with the model calculation of Bao and Käppeler.

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1. Introduction

Abundances of the s-only nuclei, $^{80}$Kr and $^{82}$Kr, are sensitive to the s-process branching at $^{79}$Se. Major fractions of these nuclei originate from the weak s-process which takes place in the core-helium burning of massive stars with a neutron source of the $^{22}$Ne($\alpha$,n) reaction [1]. The stellar condition for the nucleosynthesis of the weak s-process component can be locally examined provided that a competition between $\beta^-$ decay and neutron capture at $^{79}$Se is highly sensitive to the stellar temperature and neutron density. The half life of $^{79}$Se in the ground state is less than 65,000 years [3] and may be greater than the assumed value, 1,700 years [2]. In contrast to the long half life of the ground state, the first excited state of $^{79}$Se at 96 keV, which is thermally populated in the stellar condition, undergoes $\beta^-$ decay to $^{79}$Br with the half life 7000 minutes[2]. As a result, the stellar $\beta$-decay rate is highly sensitive to temperature [2, 4]. On the other hand, the stellar neutron capture rate for $^{79}$Se depends on both the neutron density $n_n$ of the relevant stellar site and neutron capture cross sections $\sigma_{n\gamma}$. Up until now, $\sigma_{n\gamma}$ has remained experimentally unknown though a direct measurement is planned at the CERN n-TOF facility in the future [5].

We have measured photoneutron cross sections ($\sigma_{\gamma n}$) for $^{80}$Se to evaluate $\sigma_{n\gamma}$ for $^{79}$Se within the framework of the Hauser-Feshbach model. In the model calculation, the experimental $\sigma_{\gamma n}$ is used as constraints on the low-energy E1 $\gamma$ strength function for $^{80}$Se. Uncertainties associated with the nuclear level density are taken into account. It is to be noted that the present $\sigma_{\gamma n}$ constitutes the basic nuclear data for nuclear transmutation of a long-lived fission product $^{79}$Se.

2. Experiment

Beams of quasi-monochromatic $\gamma$ rays were produced in the energy range of 9.98 - 11.80 MeV from laser Compton scattering (LCS) in the electron storage ring TERAS at AIST. The LCS $\gamma$-ray beams were used to irradiate a sample of 1003.3g $^{80}$Se enriched to 99.95% that is encapsulated in an aluminum container. A Nd:YVO$_4$ Q-switch laser was operated at 20 kHz in the second harmonics ($\lambda = 532$ nm). The $\gamma$-ray beams had the same macroscopic time structure of 80 ms beam-on and 20 ms beam-off as that of the laser. The $^{80}$Se sample was mounted at the center of a 4$\pi$-type neutron detector consisting of 20 $^3$He counters embedded in a polyethylene moderator in a triple-ring configuration. Background neutrons were detected during the 20 ms beam-off. The neutron detection efficiency is more than 56% in the neutron energy range below 1 MeV. The so-called ring ratio technique [6] was used to determine the average neutron energies. The LCS $\gamma$ beam was measured with a 120% high-purity germanium detector (HPGe). The energy distribution of the LCS beam was determined by a least-squares analysis of the response function of the HPGe detector. The LCS beam was monitored with a large volume (8" in diameter $\times$ 12" in length) NaI(Tl) detector. Pile-up spectra were used to determine the number of the incident LCS $\gamma$ rays. Photoneutron cross sections were determined at the average $\gamma$-ray energies with the Taylor expansion method [7]. The systematic uncertainty for the cross section is 4.4% whose breakdown is 3.2% for the neutron detection efficiency and 3% for the number of incident $\gamma$ rays.

3. Photoneutron cross sections for $^{80}$Se

Results of the present photoneutron cross section measurement for $^{80}$Se are shown in Fig. 1.
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Figure 1: The present result of photoneutron cross sections for $^{80}\text{Se}$ near the neutron threshold. For comparison, the data of Carlos et al. [10] taken with the positron annihilation $\gamma$ rays are shown.

Figure 2: Stellar neutron capture rates for $^{79}\text{Se}$ evaluated within the framework of the Hauser-Feshbach model by using the present photoneutron cross section for $^{80}\text{Se}$ as constraints on the E1 $\gamma$ strength function.

One can see that the present $\sigma_{\gamma n}$ are significantly smaller than those of the previous measurements near the neutron threshold. Hauser-Feshbach model calculations were carried out based on different ingredients of model parameters: Lorentzian [8] and QRPA [9] models for the E1 $\gamma$ strength function and back-shifted Fermi gas (BSFG) and combinatorial models[11, 12] for the nuclear level density. Two calculations with the Lorentz - BSFG and the combinatorial - QRPA model parameters satisfactorily reproduce the present cross sections near the neutron threshold.
4. Stellar neutron capture rates for $^{79}$Se

Neutron capture cross sections were evaluated for $^{79}$Se by using the same ingredients of the model parameters that were found for the present cross section for $^{80}$Se($\gamma,n$)$^{79}$Se. Fig. 2 shows $\langle \sigma_{n\gamma} \rangle$ as a function of the stellar temperature in units of keV. The result with the BSFG-Lorentz model parameters is similar to that of Bao and Käppeler [13], whereas the reaction rate is enhanced with the combinatorial-QRPA model parameters. The difference in the two model calculations stems from their different behaviors of the E1 $\gamma$ strength function below the neutron separation energy and the nuclear level density. Implications of the present reaction rates for the stellar condition for the weak s-process component will be investigated in the future.

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References