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Evaluation of neutron capture cross section on ^{205}Pb with photonuclear data

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Abstract. The neutron capture cross section of long-lived radioactive ^{205}Pb is derived by using the nuclear reaction calculation code CCONE, based on photonuclear data. The present result is smaller than that of TENDL-2015 by a factor of 4. The derived Maxwellian averaged capture cross section (MACS) is the smallest compared to the existing data. The produced amount of ^{205}Pb is explored with a simulated neutron flux in the Pb-Bi eutectic (LBE) target. The continuous use of the system in 25 years creates ^{205}Pb with about 6 kg at maximum in the LBE (including natural Pb of 10^3 kg). The impact of the derived MACS on the stellar nucleosynthesis is investigated. It is found that the abundance of Tl is slightly enhanced due to the increase in the remaining abundance of ^{205}Pb.

1 Introduction

The use of Pb-Bi eutectic (LBE) as a target and coolant is under consideration for the accelerator-driven system (ADS) of Japan Atomic Energy Agency (JAEA). The minor actinides are installed and transmuted into short-lived nuclides in a subcritical reactor [1]. The proton beam is injected into the LBE target. Then, ^{205}Pb is formed from the neutron capture reaction on ^{204}Pb in the target. The radioactive ^{205}Pb has long half-life of 17.3 Myr, and thus it has long-lasting radiotoxicity. The ^{205}Pb amount produced in the operation of reactor should be taken into account, in order to use the target for a long period of time, although the natural abundance of ^{204}Pb is only 1.4 % in Pb. For this purpose, it is necessary to know the reliable neutron capture cross section on ^{205}Pb as well as that of ^{204}Pb.

The neutron cross sections of ^{205}Pb are only included in evaluated nuclear data libraries of JEFF-3.2 [2] and TENDL-2015 [3]. Koning et al. [4] evaluated the nuclear data of Pb for investigating their impact on ADS design. However, the data were not based on experimental data. Its direct measurement has difficulty in a sample production. Instead, a photonuclear measurement on ^{206}Pb was planed for our group to derive the information of photon strength function (PSF) strongly related to photon absorption and emission, since the accurate determination of PSF is important to obtain reliable capture cross section.

On the other hand, the study of an slow neutron capture process (*s*-process) in a low-mass asymptotic giant branch (AGB) star is interested in the Pb-Bi region [5]. The timescale of neutron capture reaction on ^{205}Pb gives an influence on the remaining abundance of ^{205}Tl after the termination of the *s*-process. Hence, for accurate prediction of abundance pattern observed at the surface of extrinsic AGB stars, the determination of neutron capture cross section of ^{205}Pb is also requisite.

2 Photonuclear experiment

Photon scattering experiment was performed at the γELBE facility of Helmholtz-Zentrum Dresden-Rossendorf (HZDR). The bremsstrahlung photons were generated by electrons with kinetic energy of 10.5 MeV, hitting Nb foil. The ^{206}Pb target was used with mass of 3940 mg and enrichment of 99.3 %. The photons scattered from the target were measured by 4 HPGe detectors placed at 90 and 127 degrees. The measurements at the two angles were needed to separate spin states ($J = 1$ or 2) excited from the 0^+ ground state by photons. As a result, 85 and 3 excited levels were identified as the $J = 1$ and $J = 2$ states, respectively, below 8.2 MeV from the measured photon spectra. The integrated cross sections were derived from the intensity of spectrum and were used for the evaluation of photonuclear cross sections. The details of the experiment and analysis are found in Ref. [6].

3 Calculation models

Evaluation of photon and neutron-induced cross sections was made by the nuclear reaction calculation code CCONE developed at JAEA [7]. The neutron optical model was adopted with spherical potential for Pb isotopes [4]. The potential parameters for ^{205}Pb were assumed to be the same as those of ^{206}Pb, since the parameters are considered not to have a large change among the neighbor isotopes. The statistical process of the CCONE code is based on the Hauser-Feshbach model. The excited

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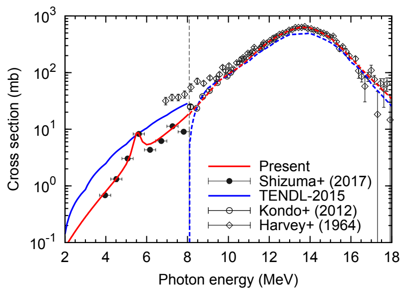

Figure 1. Comparison of the evaluated photonuclear data for ^{206}Pb with available experimental data. The dashed and solid lines represent the (γ,n) reaction and photoabsorption cross sections, respectively. The vertical line corresponds to the threshold energy of (γ,n) reaction.

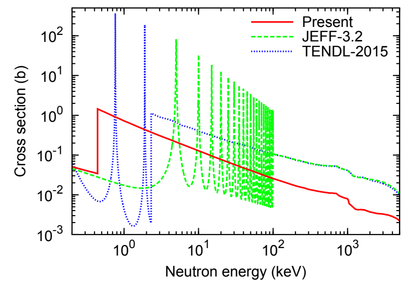

Figure 2. Comparison of the evaluated neutron capture cross section for ^{205}Pb with those of available nuclear data libraries.

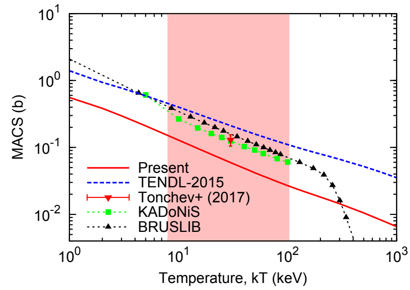

Figure 3. Comparison of the Maxwellian averaged neutron capture cross section for ^{205}Pb with available MACS data.

energy, spin-parity and de-excitation photon energy of discrete levels were retrieved from the RIPL-3 database [8]. Above the adopted excited level, the Gilbert-Cameron formalism [9] with the Fermi-gas model [10] was applied to describing a nuclear level density. The PSF is important to determine the excitation and de-excitation intensities by photons. The PSF form for the E1 radiation was employed from the standard Lorentzian model with energy-dependent damping width. The standard Lorentzian model was adopted for M1 and E2 radiations [11]. The two-component exciton model was also incorporated for the preequilibrium process [12, 13].

4 Results

4.1 Photonuclear cross sections

There are experimental data for two types of photon-induced reaction on ^{206}Pb below 14.8 MeV. They were used for the evaluation of photonuclear data. The ^{206}Pb(γ,1nx) reaction cross sections have been measured with annihilation and laser-Compton scattering photons [14, 15]. The data of Ref. [14] were multiplied with a factor of 1.22, recommended by Ref. [16]. The photoabsorption cross section was evaluated below 8.1 MeV which is the threshold energy of (γ,n) reaction. In this region the integrated cross section of (γ,γ') reaction obtained at the γELBE facility was averaged with 550 keV energy bin and was employed to the photonuclear reaction evaluation. The parameters of giant dipole resonance (GDR) were fixed from these measured data. The enhancement of cross section was observed around 5.5 MeV. It was reproduced by giving an additional contribution to the GDR parameters.

Figure 1 shows the comparison of the present results with measured data and TENDL-2015[1] for the (γ,1nx) and photoabsorption reaction cross sections. The present evaluation provides the cross sections consistent with both of the measured reaction data. The data of TENDL-2015 has smaller and larger cross sections, compared with measured data of (γ,1nx) and photoabsorption reactions, respectively.

4.2 Neutron capture cross sections

The fixed PSF was applied to calculate the neutron capture cross section of ^{205}Pb. The obtained result is shown in Fig. 2, in which the comparison is done with the cross sections of JEFF-3.2 and TENDL-2015. It should be noted that the resonance cross sections in both libraries are artificially generated. The present cross section is by a factor of 4 smaller than that of TENDL-2015 at 100 keV.

The Maxwellian averaged cross section (MACS) was further derived from the present neutron capture one. This MACS is compared with the data of KADoNiS [17], BRUSLIB [18] and Tonchev et al. [19] as well as that calculated from TENDL-2015 in Fig. 3. It is found that the present MACS is the smallest among the data mentioned above. The difference between the MACSs of Tonchev et al. and ours is unexpectedly large despite having the similar idea for the derivation of the cross section. Tonchev et al. incorporated the contributions of pygmy dipole resonance and core polarization in the gamma-ray transition strength for calculating the neutron capture cross section. Their strengths are considered to be higher than that of the additional contribution introduced in the present work.

[1]The production cross section of ^{205}Pb was used since TENDL-2015 does not include the partial cross sections for (γ,1nx) reaction. The (γ,np) and (γ,$n\alpha$) reaction cross sections are negligible in this energy region.

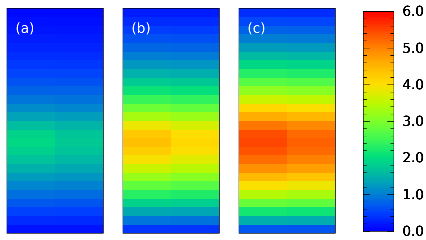

Figure 4. Produced amount (in unit of kg) of ^{205}Pb in the LBE target in the irradiation periods of (a) 5 yrs., (b) 15 yrs. and (c) 25 yrs.

5 Discussion

5.1 ADS

The LBE material is planned to be used as the target in the ADS of JAEA. The neutron capture on ^{204}Pb produces a radioactive ^{205}Pb when the target is bombarded with proton beam and the spallation reaction generates neutrons. A simulated neutron spectrum in the system was used to estimate the produced amount of ^{205}Pb. The condition of the proton beam current is assumed to be 8.7 mA. In this case the neutron flux was 10^{14-16} cm^{-2} sec^{-1}. Figure 4 shows the produced amount of ^{205}Pb in the LBE in the irradiation periods of 5, 15 and 25 years, when the LBE is fixed at the same position in this work. It is found that the 25 years-irradiation makes the ^{205}Pb amount by about 6 kg at maximum in the target with natural Pb of 10^3 kg.

5.2 Stellar nucleosynthesis

The neutron capture reaction on ^{205}Pb is relevant to the *s*-process nucleosynthesis in an AGB star. In this subsection, the impact of the smallest MACS on the s-process was investigated with a canonical s-process model. The MACS library was taken from data based on JENDL-4.0 [20], supplemented with KADoNiS. When the MACS of ^{205}Pb was changed to that of KADoNiS and TENDL-2015, the abundance difference is only found in ^{205}Tl because ^{205}Pb left after the termination of neutron exposure decays to ^{205}Tl. The uncertainty of [Tl/Fe] abundance coming from the difference of the adopted MACS is 0.03 dex (decimal exponent), which is smaller than observational uncertainties (note that $[A/B] \equiv \log_{10}(N_A/N_B) - \log_{10}(N_A/N_B)_{\odot}$, where N_A and N_B are the number of elements A and B, respectively. The symbol $\odot$ stands for the number in the Sun). Hence, it may be still difficult to judge which MACSs of ^{205}Pb are valid from observations of stellar surface composition.

6 Summary

Neutron capture cross section of long-lived radioactive ^{205}Pb (17.3 Myr) was evaluated with photonuclear data by applying the CCONE code. The PSF of ^{205}Pb was fixed, comparing the photonuclear cross sections with the experimental data. The evaluated neutron capture cross section on the basis of the determined PSF is by a factor of 4 smaller than TENDL-2015. In the ADS point of view, the produced amount of ^{205}Pb is about 6 kg at maximum in an installed LBE target (natural Pb of 10^3 kg loaded) even in 25 years-use. In the astrophysical point of view, the impact of the neutron capture cross section can be seen in Tl abundance, but is small. The present evaluation result is planned to be included in the next general purpose library of JENDL.

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