The measurement of neutron capture cross section of ^{62}Ni and nucleosynthesis of heavy elements

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Abstract

We measured the keV neutron capture cross section of ^{62}Ni in the energy range from 5.5 to 90 keV by using an anti-Compton NaI(Tl) spectrometer. The Maxwellian averaged cross section (MACS) is derived to be 37.2 ± 3.2 mb. This is 3.0 times larger than the value used in the calculation of s-process nucleosynthesis in massive stars.

1. Introduction

The overproduction of Ni isotopes has been a long standing problem in the calculations of s-process nucleosynthesis in massive stars [1], and the problem still remains in the recent nucleosynthesis calculation from the onset of central hydrogen burning through explosion as Type II supernovae [2]. Among the Ni isotopes, ^{62}Ni has the largest overproduction factor. The origin of this problem is claimed to be due to nuclear physics inputs such as MACS of the Ni isotopes [2]. The MACS of ^{62}Ni used in the calculation is 12.5 ± 4 mb at 30 keV [3], which is obtained by considering the interference effect of a narrow subthreshold resonance at E_R=-0.077 keV with the direct s-wave capture process. Theoretically, the neutron cross section of ^{62}Ni has been calculated by taking into account not only s-wave but also p-wave neutron capture process [4]. The resultant MACS is 40.3 ± 5 mb at 30 keV. Hence, we aimed at measuring the cross section of ^{62}Ni(n,γ) ^{63}Ni at stellar energy, and also searching for direct γ-rays due to the possible p-wave neutron capture reaction of ^{62}Ni.

2. Experimental procedure

We measured the cross section of the ^{62}Ni(n,γ)^{63}Ni reaction by using pulsed keV neutrons. The neutrons were produced by the ^{7}Li(p,n)^{7}Be reaction using a pulsed proton beam provided from the 3.2 MV Pelletron accelerator of the Research Laboratory for Nuclear Reactors at Tokyo Institute of Technology. We cyclically changed enriched

(96.3%) ^{62}NiO, gold (Au) and blank samples to smear out any possible changes of the measuring system. A weight of the ^{62}Ni sample was 2.52g. Gold was used for normalization of the absolute capture cross section of ^{62}Ni [5]. The event rates of these three runs were connected by the neutron counts detected by the efficiency calibrated ^{6}Li –glass detector. We used an anti-Compton NaI(Tl) spectrometer to detect a prompt γ-ray from the ^{62}Ni(n,γ)^{63}Ni reaction [6]. The spectrometer was set at 125.3° with respect to the proton beam direction, where the second Legendre polynomial is zero and thus γ-ray yields detected at this angle provide an angle integrated cross section of the ^{62}Ni(n,γ)^{63}Ni reaction for a dipole transition. We measured a time-of-flight (TOF) spectrum to obtain background free (net) γ-ray yields from the ^{62}Ni(n,γ)^{63}Ni reaction as a function of the neutron energy by a central NaI(Tl) detector of the NaI(Tl) spectrometer.

3. Results

The measured TOF spectrum for ^{62}NiO is shown in Fig.1, where the sharp peak at around 610 channel is due to the γ-rays from the ^{7}Li(p,γ)^{8}Be reaction at the neutron production target position. The foreground and background γ-ray spectra from the ^{62}Ni(n,γ)^{63}Ni reaction were obtained by putting the gates in the proper regions on the TOF spectrum. The net spectrum for the neutron energy range from 5.5 to 90 keV is shown in Fig.2. We observed the intense 6.8 MeV discrete γ-ray feeding from the keV neutron capture state of ^{62}Ni to the ground state ($J^{\pi}=1/2^{-}$). However, the cascade γ-rays feeding from the predicted p-wave capture state of ^{62}Ni to the ground state in ^{63}Ni via the excited state ($J^{\pi}=1/2^{+}$) at E_x=2.955 MeV [4] were not observed.

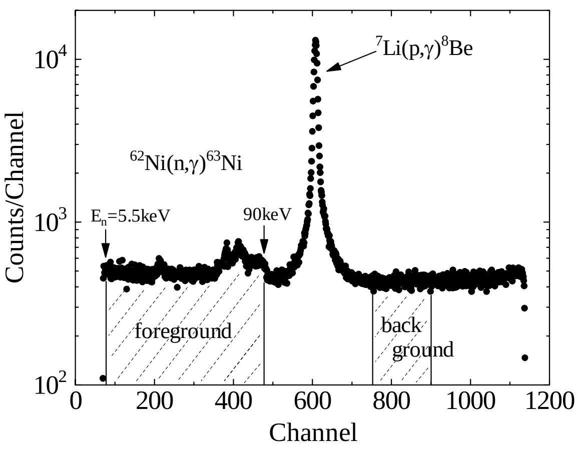

Fig.1: TOF spectrum measured by a NaI(Tl) detector for ^{62}NiO sample.

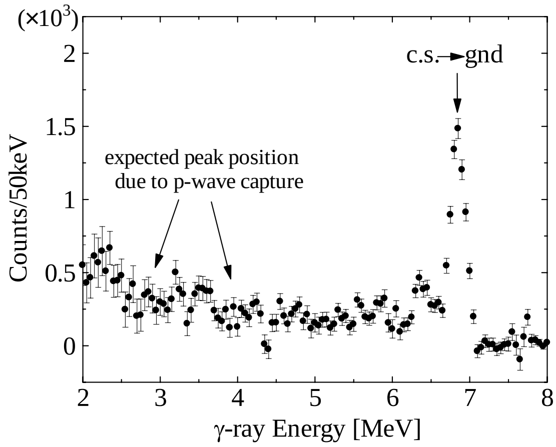

Fig.2: Background subtracted γ-ray spectrum for ^{62}NiO sample.

We employed the pulse height weighting technique to obtain the γ-ray yield in the net spectrum [7]. Using the γ-ray yields the capture cross-section σ_γ(Ni) was obtained as follows.

$$\sigma_\gamma(Ni) = \frac{T_{Au}}{T_{Ni}} \frac{P_{Ni}}{P_{Au}} \frac{C_{Au}}{C_{Ni}} \cdot \frac{(r^2 n)_{Au}}{(r^2 n)_{Ni}} \frac{Y_\gamma(Ni)}{Y_\gamma(Au)} \cdot \sigma_\gamma(Au)$$

Here, T and P are the number of the neutron counts measured by the ^{6}Li-glass detector during the measurements of the sample, and the neutron transmission of the sample, respectively, r and n are the radius and thickness (atoms/barn) of the sample, respectively, Y(Au) and σ(Au) are the γ-ray yield and the absolute capture cross section for the sample, respectively. A correction factor C was calculated using the Monte-Carlo code, TIME-MULTI [8]. The total capture cross section thus obtained is shown in Fig.3.

In order to derive the MACS we compared the present results to the evaluated cross section of the ^{62}Ni(n,γ)^{63}Ni reaction, JENDL-3.3. From this comparison we multiply the cross section given by JENDL-3.3 by a factor 2 below 5.5 keV and by a factor 1.5 above 90 keV. The MACS thus obtained is shown in Fig.4. The MACS at 30 keV is derived as 37.0 ± 3.2 mb, which is larger than the value used in the s-process nucleosynthesis in massive stars by a factor of three. Since the overproduction factor of ^{62}Ni is about three, the present MACS could significantly influence the factor and may solve the problem.

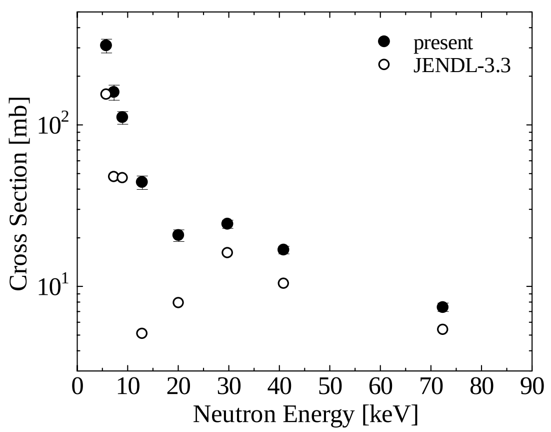

Fig.3: Neutron capture cross section of ^{62}Ni.

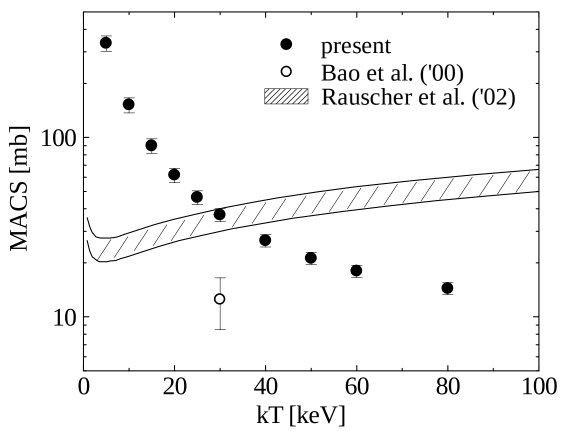

Fig.4: Maxwellian averaged cross section of ^{62}Ni.

4. Summary

The neutron cross section of the ^{62}Ni(n,γ)^{63}Ni reaction was measured precisely at astrophysically relevant energy. The MACS was derived as 37.0 ± 3.2 mb at 30 keV. This present value could solve the long standing problem of the overproduction of ^{62}Ni. The predicted p-wave neutron capture process turned out to play a minor role in the present energy range. The evaluated value by JENDL played an essential role to obtain the neutron capture cross section.

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