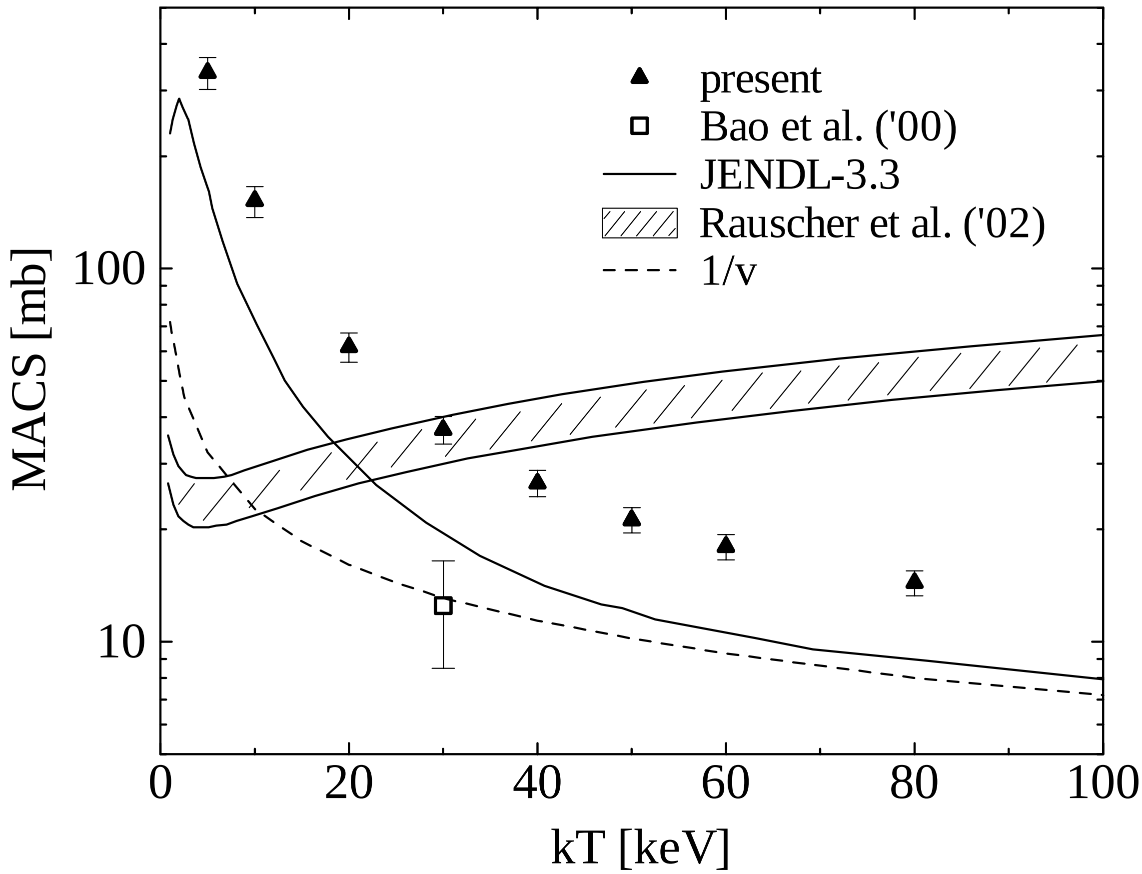


Figure 1: Maxwellian averaged neutron capture cross section (MACS) of $^{62}$Ni. Here the black triangle is the MACS estimated using the present result, the open square is the MACS by Bao et al., the band indicated by the shadow line is the calculated one, the solid is the evaluated one by JENDL, and the dotted line is the value estimated assuming a 1/v law.

# keV neutron capture reaction of $^{62}$Ni and necleosynthesis of heavy elements

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It has been believed that the construction of stellar models of nucleosynthetic yields of massive stars of various metallicities is quite important to finally construct models for chemical evolution of galaxies [1]. In the recent nucleosynthesis yields caluculation of massive stars of solar metallicity from the onset of central hydrogen burning through explosion as type II supernovae [2] several Ni isotopes are overproduced. Among these Ni isotopes the most overproduced nucleus is $^{62}$Ni. Note that the calculated nucleosynthetic yields of most isotopes from $A$ = 16 to $A$ = 90 agree with the solar abundances. The overproduction of Ni isotopes has been a long standing problem in the calculations of slow (s) process nucleosynthesis in massive stars [3]. The origin of this problem is considerd to be caused by residual uncertainties in the steller models and/or in the nuclear physics inputs such as the Maxwellian averaged neutron capture cross section (MACS) of the Ni isotopes [2]. The MACS of $^{62}$Ni used in the recent nucleosynthesis caluculation was 12.5 $\pm$ 4 mb at $kT$ = 30 keV. This value was obtained by extrapolating the measured thermal neutron capture cross section to 30 keV and by considering the interference effect of the subthreshold resonance at $E_R$ = - 0.077 keV in $^{63}$Ni with the direct s-wave capture process of $^{62}$Ni [4]. Experimentally the keV neutron capture cross section of $^{62}$Ni was measured [5] [6] and the MACS was reported as being 26 $\pm$ 5 mb at 30 keV. Theoretically the neutron capture cross section of $^{62}$Ni has been calculated by taking into account not only the non-resonant direct s-wave but also the non-resonant p-wave neutron capture process [7]. The resultant MACS is 40.3 $\pm$ 5 mb at $kT$ = 30 keV. This large value is mainly due to the non-resonant direct p-wave capture process of $^{62}$Ni. Although the dominance of the p-wave process is known for the keV neutron capture reactions in light nuclei [8] [9] [10] [11], an experimental work to study the role of the p-wave process has not yet been performed for the keV neutron capture reaction of intermediate mass nuclei like Ni isotopes. Hence, in the present study we aimed at measuring the neutron capture cross section of $^{62}$Ni at stellar neutron energy, and also searching for cascade $\gamma$-rays due to the possible p-wave neutron capture reaction of $^{62}$Ni.

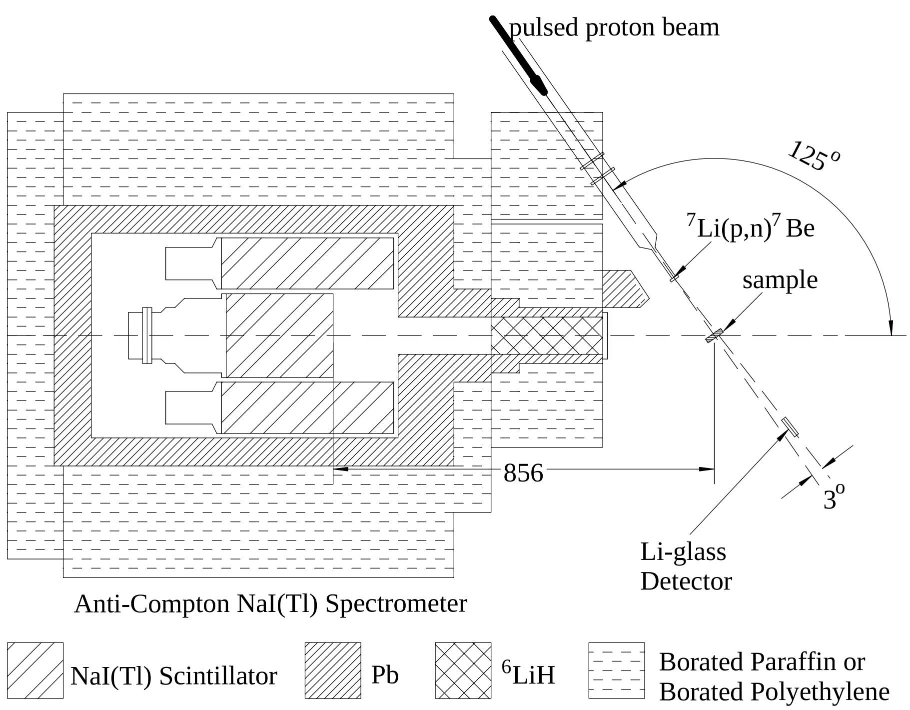


Figure 2: A schematic view of an experimental setup

We measured the neutron capture cross section of $^{62}$Ni 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 uesd an anti-Compton NaI(Tl) spectrometer [12] to detect a prompt $\gamma$-ray from the $^{62}$Ni(n,$\gamma$)$^{63}$Ni reaction. A schematic view of an experimental setup is shown in Figure 2. We measured a time-of-flight (TOF) spectrum to obtain background free (net) $\gamma$-ray yields from the $^{62}$Ni(n,$\gamma$)$^{63}$Ni reaction as a function of the neutron energy by the NaI(Tl) spectrometer. We cyclically changed three samples of the 2.52 g nickel oxide (96.3 % enriched in $^{62}$Ni), gold (Au) and blank samples to smear out any possible changes of the measuring system. Au was used for normalization of the absolute neutron capture cross section of $^{62}$Ni, since the cross section of Au is known with an uncertainty of only 3-5 % [13]. The event rates of these runs were connected by the neutron counts detected by an efficiency calibrated $^{6}$Li-glass detector.

The TOF spectrum measured by the NaI(Tl) detector for the $^{62}$NiO sample is shown in Figure 3. Here, the sharp peak at around 610 channel is due to the $\gamma$-ray from the $^{7}$Li(p,$\gamma$)$^{8}$Be reaction at the neutron production target position. The foreground (FG) and background (BG) $\gamma$-ray spectra from the $^{62}$Ni(n,$\gamma$)$^{63}$Ni reaction were obtained by putting the gates in the proper regions on the TOF spectrum, respectively. The net spectrum for the neutron energy range from 5.5 to 90 keV is shown in Figure 4. We observed the intense 6.8 MeV discrete $\gamma$-ray transition due to the direct neutron capture into the ground state ($J^{\pi} = 1/2^{-}$) in $^{63}$Ni. However, the cascade $\gamma$-ray transitions from the predicted p-wave capture state of $^{62}$Ni feeding to the ground state in $^{63}$Ni via the excited state ($J^{\pi} = 1/2^{+}$) at $Ex = 2.955$ MeV [7] were not observed. We observed the 1.17 MeV and the 10.6 MeV $\gamma$-rays from the $^{61}$Ni(n,$\gamma$)$^{62}$Ni reaction. Note that the impurity of $^{61}$Ni is 1.8 % in the $^{62}$NiO sample. The present 10.6 MeV $\gamma$-ray intensity relative to the 1.17 MeV one was 0.045 $\pm$ 0.009, which is consistent with the value of 0.049 for thermal neutron capture of $^{61}$Ni [14] within the experimental uncertainty. Hence, the neutron capture reaction of $^{61}$Ni is considered to proceed via an s-wave capture process, and its cross section can be obtained assuming the s-wave capture process and using the $\gamma$-ray branching ratio obtained for thermal neutrons. The obtained cross sections are 370 $\pm$ 350 mb, 120 $\pm$ 65 mb and 37 $\pm$ 14 mb at the average neutron energy of 8, 16 and 37 keV, respectively. The MACS of $^{61}$Ni was calculated by normalizing the cross section of the JENDL-3.3 to the present value at the average neutron energy of 40 keV, which agrees with the value evaluated in the JENDL-3.3.

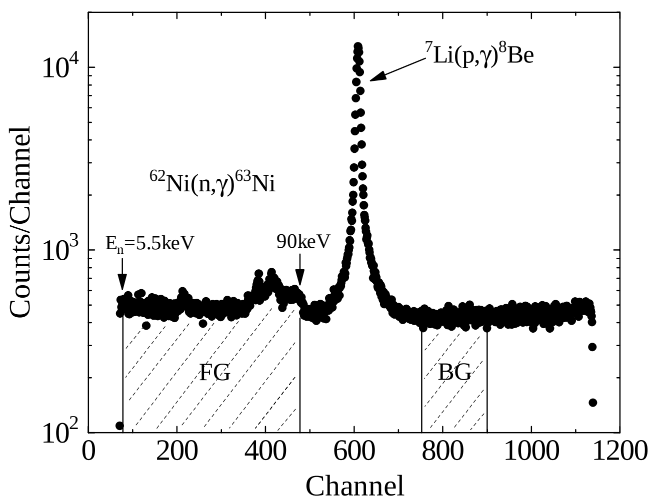


Figure 3: The TOF spectrum measured by a NaI(Tl) detector for the $^{62}$NiO sample.

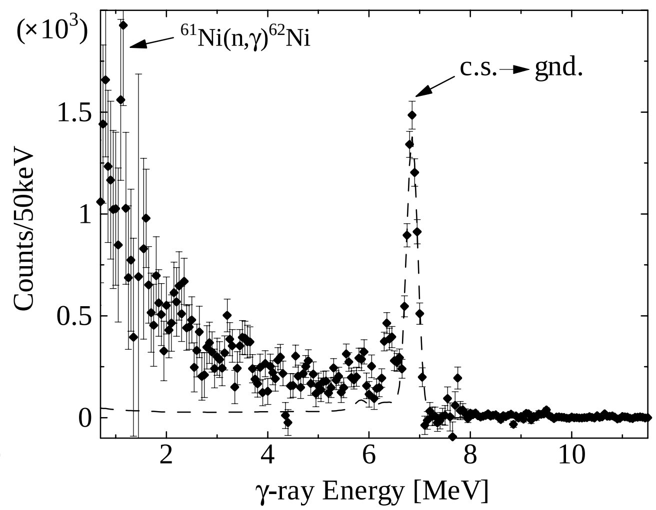


Figure 4: Background subtracted $\gamma$-ray spectrum for the $^{62}$NiO sample.

We employed the pulse height weighting technique to obtain the $\gamma$-ray yield in the net spectrum [15]. The derived total capture cross section is shown in Figure 5. In order to derive the MACS we need the neutron capture cross section below 5.5 and above 90 keV. Hence, we compared the present results to the evaluated cross section of the $^{62}$Ni(n,$\gamma$)$^{63}$Ni reaction, JENDL-3.3. From this comparison we multiplied the neutron capture cross section of $^{62}$Ni given by JENDL-3.3 by a factor 2 below 5.5 keV and by a factor 1.5 above 90 keV. The resultant MACS is shown in Figure 1. The MACS at $kT = 30$ keV was derived to be 37.0 $\pm$ 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 solve the long standing problem of the overproduction.

The neutron capture cross section of $^{62}$Ni(n,$\gamma$)$^{63}$Ni reaction was measured precisely at stellar neutron energy. The MACS was derived to be 37.0 ± 3.2 mb at $kT$ = 30 keV. The present value could solve a long standing problem of the overproduction of $^{62}$Ni. In the $^{62}$Ni(n,$\gamma$)$^{63}$Ni reaction the s-wave neutron capture process was dominant, but the predicted p-wave neutron capture process turned out to play a minor role in the present energy range. The present work is published in elsewhere [16].

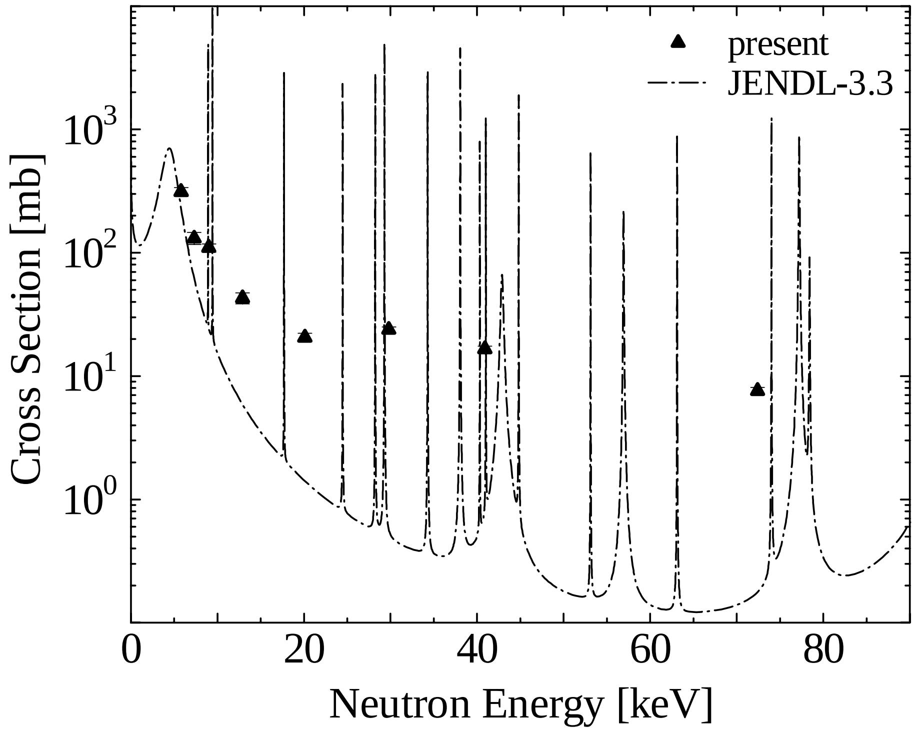


Figure 5: Neutron capture cross section of $^{62}$Ni.

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