New measurement of the astrophysically important reaction ^{62}Ni(n,γ) at n_TOF

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The neutron capture cross section of the reaction ^{62}Ni(n,γ)^{63}Ni was measured over a wide energy range from 1 eV to 1 MeV at the neutron time-of-flight facility n_TOF installed at CERN. Preliminary results show that due to the unique experimental setup a high energy resolution was achieved and a number of resonances can be resolved also at high energies (tens to hundreds of keV). This measurement will allow a precise determination of the capture cross section and Maxwellian-Averaged Cross Sections (MACS) and be a step forward for understanding nucleosynthesis processes in stars.

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1. Introduction

Elements heavier than Fe are dominantly produced via neutron capture reactions. Two processes contribute about equally to the overall abundance pattern, the so-called rapid neutron capture (r-process) and the slow neutron capture (s-process). The r-process, taking place in explosive environments (e.g. supernovae) is characterized by high neutron fluxes, hence high reaction rates. Therefore, the nucleus subsequently captures neutrons before it is able to decay and the generation of elements takes place close to the neutron drip-line. On the other hand, in s-process scenarios neutron densities are much smaller and the generation of an unstable nucleus is followed by its β-decay towards the valley of stability. The s-process can be divided into two components, corresponding to different stellar environments and neutron densities. The main component is responsible for the production of elements between Zr and Bi. The neutron densities in the corresponding stellar environment (thermally pulsing AGB stars) are sufficiently high to reach an equilibrium condition between neutron shell closures $\sigma(n,\gamma) \times N = const$, which means that the abundance N of a particular isotope depends only on its neutron capture cross-section $\sigma(n,\gamma)$. For the elements below A=90 however, the weak component of the s-process plays a significant role, for which the equilibrium condition is not fullfilled. A change in the neutron capture cross-section influences also abundances of the following isotopes. The reliabilty of present neutron capture cross sections have been questioned after observations of elemental abundances in Ultra-Metal-Poor stars. These stars show a robust r-process pattern but systematic deficiencies between observed and predicted values for masses below A=90 were found ([1],[2]). Since the predicted abundances are calculated by subtracting the s-process contribution from the solar abundances, neutron capture cross sections are a possible source of error.

In 2009, a campaign to measure accurate neutron capture cross sections of all stable Fe and Ni nuclei which represent the seed nuclei of the s-process, has been launched at the neutron time-of-flight facility n_TOF at CERN. In the following the measurement of ^{62}Ni(n,γ)^{63}Ni and the present status of the analysis are described.

2. Measurement

The experiment was performed at the n_TOF facility at CERN. n_TOF is based on a spallation neutron source in combination with a 185 m flight path. A highly intense, white neutron spectrum, of energies ranging from subthermal to 10 GeV is produced by 20 GeV/c protons impinging on a massive Pb-target surrounded by water which serves as moderator and coolant. The protons are provided by the Proton Synchrotron with a nominal intensity of 7×10^{12} protons per pulse and a pulse width of 7 ns (for further reading see [3]). The capture yield is determined by measuring the prompt γ-emission of the compound nucleus after neutron capture, the neutron energy is measured via its time-of-flight.

For this measurement a pair of liquid scintillation detectors filled with deuterated benzene (C_6D_6) were used. The detectors have been optimized for low neutron sensitivity [4]. The disc sample with a mass of 2 g and a diameter of 2 cm was 97.95% enriched in ^{62}Ni. To monitor the neutron flux several detectors were used, e.g. a parallel plate fission chamber loaded with ^{235}U and four

Silicon-detectors, the latter detecting the reaction products of ^{6}Li(n,α)^{3}H in a thin Li foil placed in the neutron beam.

3. Data analysis

In a capture experiment, the quantity extraced is the capture yield

$$Y = f_N \frac{C - B}{\varepsilon \Phi}$$

where C is the number of capture events counted by the detector, B is the background, ε the efficiency, Φ the neutron flux and f_N a normalization factor, which has to be applied since the sample does not cover the entire neutron beam. The yield is related to the capture cross section $\sigma_{n,\gamma}$ with $Y = (1 - \exp(-n\sigma_{tot})) \times \sigma_{n,\gamma}/\sigma_{tot}$, where n is the target thickness in atoms per barn and σ_{tot} the total cross section.

The C$_6$D$_6$-setup has low detection efficiency (at most one γ-ray per cascade). Under these cirumstances it is possible to utilize the pulse-height-weighting-technique [5], where a pulse-height dependent weight is applied to each recorded signal in order to achieve a detection efficiency for capture events corresponding to the capture energy (neutron kinetic energy plus neutron separation energy). The weights are determined by performing detailed Monte-Carlos simulations of the detector response including the whole experimental setup.

The background at n_TOF is dominated by three effects: (i) neutrons elastically scattered and captured afterwards in the surrounding material or detector (most effective from 1 eV to 200 eV), (ii) scattered γ-rays, which are produced in the target station mainly via neutron capture on hydrogen (dominating from 200 eV to 200 keV) and (iii) γ-rays from (n,n'γ) reactions. Since it is impossible to correct for background component (iii), the threshold for inelastic reactions limits the analysis to a neutron energy of 1.17 MeV, where the first inelastic channel of ^{62}Ni opens. The sample-independent background is obtained in runs with an empty position in the ladder of the sample changer, whereas the sample-related background components are determined in runs with adequate reference samples with the same size as the sample of interest. For neutron scattering a carbon sample was used, for γ-scattering Pb. These samples are particularly suited because in both cases the capture cross sections are extremely small and free of resonances in the energy range of interest while the respective cross sections (elastic scattering for carbon, γ scattering for Pb) are sufficiently high.

The normalization factor f_N is obtained by measuring a Au-sample of same size as the Ni. Au has a resonance at a neutron energy of $E_n = 4.9$ eV which becomes black for samples thicker than 30 μm so that all neutrons are absorbed. Because the probability for neutron capture is much higher than for neutron scattering, the capture yield is unity since even scattered neutrons are captured in the sample eventually. Therefore, the f_N is determined by fitting it to the flat top of the resonance.

## 4. Present status on MACS for ^{62}Ni(n,γ)

Available Maxwellian-Averaged Cross Sections (MACS) still show big discrepancies: Several experiments, using the time-of-flight method ([7] [8] [9]) or a combination of activation

and Accelerator-Mass-Spectrometry ([10] [11]), predict values between 20.2 and 26.8 mb for the MACS at 30 keV. The KADoNiS v0.3 compilation [12] lists a weighted average of 22.3 ± 1.6 mb as the recommended Maxwellian-Averaged cross section.

However, older compilations suggest either a lower value of 12.5 ± 4.0 mb [13] or a higher value of 35.5 ± 4.0 mb [14]. While [13] is more in favour of a calculated MACS of 10.6 ± 0.8 mb by [15], the latter is in fair agreement with the experimental value 37.0 ± 3.2 mb by [16] (time-of-flight method). It has to be noted that the compilations [13] and [14] are based on the same thermal cross section but on different assumptions concerning the extrapolation to stellar energies. Also in view of neutron resonance parameters there are major disagreements between the evaluated libraries ENDF/B-VII [17] and JENDL-4.0 [18], particularly concerning the possible existence of a subthreshold resonance at -77 eV quoted in ENDF but not in JENDL, which raises the need of a detailed resonance analysis.

5. First data from n_TOF

The new measurement at n_TOF aims to resolve these issues. Capture yield spectra of $^{62}Ni(n,\gamma)$ show a unique energy resolution over a wide energy range as illustrated in figure 1, which will allow a detailed resonance analysis.
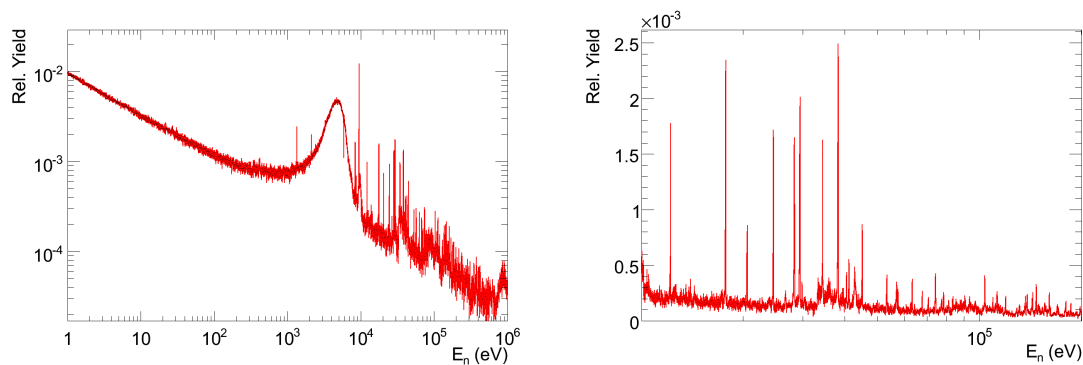

Figure 1: Weighted, unnormalized yield from 1 eV to 1 MeV. Right: Zoom into the resolved resonance region from 10 keV to 200 keV.

In a preliminary analysis the background was estimated for low energies (<10 keV) and subtracted from the yield. Figure 2 shows a comparison of the background corrected experimental yield with the yield calculated using resonance parameters of the evalutions ENDF/B-VII and JENDL-4.0, respectively. It is clearly visible, that our data show better agreement with JENDL than ENDF. After full data reduction we expect to obtain accurate values of Maxwellian-Averaged Cross Sections.

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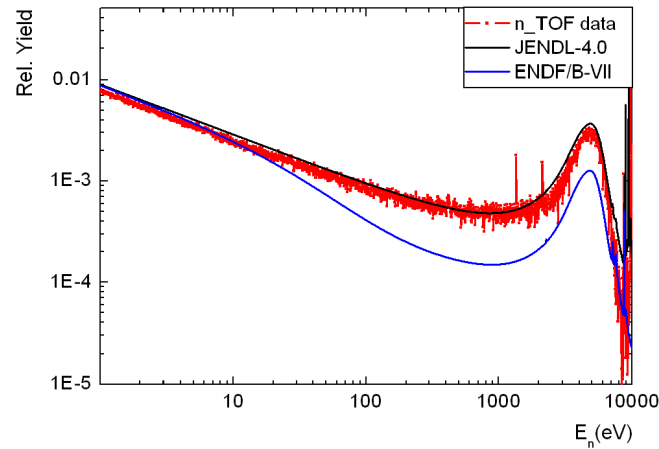
Figure 2: Capture yield of ^{62}Ni(n,γ) from 1eV to 10 keV after background subtraction compared to evaluations.

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