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Measurements of the 90,91,92,94,96 Zr (n, γ) cross-sections at n_TOF

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Neutron capture cross sections of the ^{90,91,92,94,96}Zr have been measured over the energy range from 1 eV to 1 MeV at the spallation neutron facility n_TOF at CERN in 2003. The

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innovative features of the neutron beam, in particular the high instantaneous flux, the high energy resolution and low background, together with improvements of the neutron sensitivity of the capture detectors make this facility unique for neutron-induced reaction cross section measurements with much improved accuracy. The preliminary results of the Zr measurements show capture resonance strengths generally smaller than in previous measurements.

1. Introduction

Accurate s-process analyses have attracted great interest over the last decade, thanks to the progresses in astronomical observation and in stellar modelling. The understanding of the s-process has advanced from a phenomenological description of the abundance distribution in the solar system towards a comprehensive picture, which includes the overall aspects of stellar and galactic evolution [1]. In particular, this development has shown the importance of neutron capture nucleosynthesis for probing the evolution of Red Giant stars. The success of the stellar s-process models could only be achieved by significant improvements in the neutron capture cross section data, which reached uncertainties of only a few %. At present, however, many cross section data are still missing, particularly in the mass region $A \leq 100$ as well as for neutron magic nuclei where cross sections are small and dominated by isolated resonances [2].

The Zr isotopes represent an important example for this situation. Together with strontium and yttrium, zirconium belongs to the first s-process peak in the solar abundance distribution at A≈90. Zirconium has no p-only or s-only isotopes, but neutron magic 90 Zr, as well as 91 Zr, 92 Zr, and 94 Zr, have low neutron capture cross sections and are predominantly of s-process origin. The most neutron-rich, 96 Zr, is traditionally considered to be an r-only isotope with a small but significant s-process admixture [1,3]. Its abundance is considered to be a strong indicator of the efficiency of the 22 Ne neutron source during the He shell burning episodes of thermally pulsing AGB stars. Existing (n, γ) cross sections of the Zr isotopes in the relevant energy range from 0.1 to 500 keV exhibit uncertainties larger than 10% and discrepancies of up to a factor of 2 among different measurements have been observed. The necessary improvement of these data was achieved using the unique features of the n_TOF facility, which combines excellent resolution, high instantaneous neutron flux, and low backgrounds [4].

2. Experimental setup

The measurements were performed with the n_TOF pulsed neutron beam. The neutrons are generated by spallation reactions induced by a pulsed beam of 20 GeV protons on a massive Pb target. Neutrons are slowed down in the lead and moderated in the surrounding 5 cm thick layer of cooling water. An evacuated neutron flight path with collimators at 135 and 175 m leads to the measuring station at a distance of 185 m from the spallation target. Background due to fast charged particles is suppressed by a sweeping magnet, heavy concrete walls, and a 3.5 m thick iron shielding [5]. The experimental set-up consists of two C₆D₆ detectors with minimized neutron sensitivity [6], placed perpendicular to the neutron beam at a distance of about 3 cm from the beam axis. The background due to in-beam γ -rays was reduced by placing the detectors at 9.2 cm up-

Sample	Isotopic composition $(\%)$					Thickness
	$^{90}\mathrm{Zr}$	$^{91}\mathrm{Zr}$	$^{92}\mathrm{Zr}$	$^{94}\mathrm{Zr}$	96 Zr	(atoms/barn)
⁹⁰ Zr	97.7	0.87	0.6	0.67	0.16	0.003531
$^{91}\mathrm{Zr}$	5.43	89.9	2.68	1.75	0.24	0.00181
$^{92}\mathrm{Zr}$	4.65	1.62	91.4	2.03	0.3	0.001725
$^{94}\mathrm{Zr}$	4.05	1.18	1.93	91.8	1.04	0.002536
$^{96}\mathrm{Zr}$	19.41	5.21	8.2	8.68	58.5	0.004208
$^{nat}\mathrm{Pb}$						0.0029916
$^{197}\mathrm{Au}$						0.001498

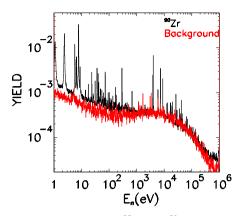
Table 1 Sample characteristics. All samples were in form of ZrO₂.

stream of the sample position. The light output of the detectors was calibrated by means of ¹³⁷Cs, ⁶⁰Co and Pu/C γ -ray sources. The calibrated neutron time of flight was used to determine the neutron energy. The detector signals were recorded with fast flash ADC using the standard n_TOF data acquisition system [7]. All zirconium samples were prepared from oxide powder, which was pressed to pellets 22 mm in diameter and encapsulated in a thin aluminium can. Additional Au and Pb samples of the same diameter were used for flux and background measurements. The relevant sample characteristics are reported in Table 1. The neutron flux was monitored 1.5 m upstream of the capture samples with a low mass flux monitor consisting of a thin layer of ⁶Li surrounded by four Si detectors outside the neutron beam [8].

3. Data analysis and results

The data analysis is based on an accurate energy calibration of the C_6D_6 detectors. Ambient and sample related backgrounds were subtracted by means of the spectra measured with an empty Al can and with the Pb sample. The absolute normalization of the capture yields has been made via the spectrum measured with the Au sample. The efficiency correction via the Pulse Height Weighting Technique (PHWT) is based on the application of a pulse height dependent weight for each single registered γ -ray to ensure that the detection efficiency is independent of the multiplicity distribution of the capture cascade. The respective weighting functions are sensitive to the experimental setup, including the investigated sample. These functions were derived by detailed Monte Carlo simulations. The capture yields are calculated according to the relation: $\sum R_i W_i = E_c \int \Phi(E) Y(E) dE$, where $\sum R_i W_i$ is the corrected energy spectrum per bunch, $\Phi(E)$ is the neutron flux per bunch, and E_c is the neutron separation energy of the isotope [9]. Figure 1 shows the capture yield for the ⁹⁰Zr sample and is compared to the overall background. The resonances analysis has been performed with the multi-level R-matrix code SAMMY [10]. The normalization of capture events has been determined with an accuracy of better than 3% by analysing the saturated 4.9 eV resonance of the Au sample.

The resonance parameters measured at n_TOF are in general smaller then previously reported. Figure 2 shows the comparison of the neutron capture kernels $g\Gamma_{\gamma}\Gamma_n/\Gamma_{tot}$ for the ⁹⁰Zr resonances with those determined in Ref. [11]. Except for a few resonances, the n_TOF results are systematically lower by 30-40%. This result may be due to the lower neutron sensitivity of the experimental setup used at n_TOF which reduces the



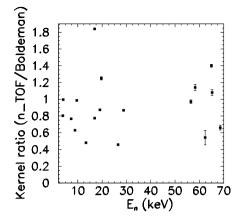


Figure 1. Yields of the $^{90}{\rm Zr}({\rm n},\gamma)^{91}{\rm Zr}$ reaction.

Figure 2. Ratio of present capture kernels for the observed resonances with the data from Ref. [11].

probability of detection of scattered neutrons, a condition particularly important here, where $\Gamma_n >> \Gamma_{\gamma}$.

4. Conclusion

The neutron capture cross sections of 90,91,92,94,96 Zr have been measured at the CERN n_TOF facility in the energy range from 1 eV up to 1 MeV. The improved experimental conditions at n_TOF allows to reduce the systematic uncertainty and to obtain the required accuracy needed in *s*-process nucleosynthesis studies.

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