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New Neutron-Induced Cross-Section Measurements for Weak *s*-process Studies

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A series of new neutron capture and transmission measurements has been undertaken at the Oak Ridge Electron Linear Accelerator (ORELA) in response to deficiencies identified in nuclear data libraries of crucial importance to the Nuclear Criticality Safety Program. New data and evaluations including covariances are required for several stable fission products as well as for materials found in mixtures with uranium. For example, chromium and nickel as constituents of stainless steel perform poorly in criticality calculations due to their relatively large neutron cross sections and substantial uncertainties in previous measurements. Therefore, new neutron-capture and total cross-section measurements are needed for ^{52,53}Cr and ^{58,60}Ni. These newly obtained data can be used not only to improve criticality calculations but also to serve as input parameters for the weak *s*-process stellar model calculations in massive stars. We will report on new experiments for these nuclides.

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1. Introduction

Recent studies [1,2] have shown that neutron-capture cross sections and their uncertainties can have a strong impact on the weak component of the *s* process in massive stars. This is especially true for nuclides with small neutron-capture cross sections, which can constrain the nucleosynthesis flow and have a substantial impact on the resulting abundances of heavier nuclides.

High-quality nuclear data are not only the input parameters for nuclear stellar model calculations but are also essential for the design and analysis of nuclear systems, such as reactor core layouts, fuel elements, and stored mixtures of nuclear waste with other materials, as well as burned fuel elements. Analysis codes for nuclear systems rely on the use of evaluated cross-section data from libraries such as ENDF/B-VII, JEFF3.1, or JENDL-3.3. Concerns about data deficiencies in some existing cross-section evaluations for nuclear criticality calculations have been the prime motivator for new cross-section measurements at the Oak Ridge Electron Linear Accelerator (ORELA). Many older neutron cross-section evaluations show signs of inadequacy or do not cover energy ranges that are important for criticality safety applications. These shortcomings may occur in the resolved and unresolved resonance regions. In addition, many evaluations for nuclides in the nuclear data libraries are missing covariance data, which are increasingly required by the more sophisticated codes to analyze and simulate nuclear systems. This shortfall can only be overcome by new experimental data included in a new evaluation.

2. Cross section measurements at ORELA

ORELA consists of a 180-MeV electron linear accelerator, a neutron-producing target, underground experimental areas and evacuated flight tubes, sophisticated detectors, and data acquisition systems. It is a highly flexible accelerator with variable repetition rate (1 to 1000 Hz) and burst width (2 to 30 ns). Neutron-induced cross-section data in the energy range from a few meV up to 50 MeV can be measured using the time-of-flight (TOF) technique.

2.1 Capture measurements

The ^{58,60}Ni neutron capture experiments were performed using the improved experimental setup at flight path 7 in the 40-m flight station. Compared to the old ORELA setup [3], the apparatus has been improved in several ways. By removing the massive Al sample changer and replacing the beam pipe with a thin carbon fiber tube, the structural material surrounding the sample and detectors was minimized in order to reduce the background due to sample-scattered neutrons (neutron sensitivity). In addition, the massive detector housings were removed and replaced with reduced-mass detector mounts. The more neutron-sensitive C_6F_6 γ-scintillators were replaced with C_6D_6 γ-scintillators, which has much lower neutron sensitivity. More details about these improvements can be found in the papers by Koehler et al. [4, 5] in which the impact of the much reduced neutron sensitivity was demonstrated in a high-resolution TOF measurement for ^{88}Sr. The knowledge acquired over past years was valuable in the construction of the new capture apparatus on flight path 6 in the 40-m flight stations. This capture system was built with emphasis on reducing mass around the sample and detectors. For both systems at flight paths 6 and 7, the pulse-height-weighting method is employed, but the code MNCP is now used for weighting function calculations instead of the Monte Carlo code EGS4. The new setup at flight path 6 was used for the natural Cr(n,γ) experiment.

Neutron-capture cross-section experiments for nickel isotopes (Fig. 1) were performed using enriched metallic samples. For ^{58}Ni, the sample was a 2.54-cm by 5.08-cm piece with an enrichment of 99.9% and a thickness of 0.03635 at/b. The 99.62% enriched ^{60}Ni sample had the same dimensions except for a thickness of 0.03598 at/b. The samples were placed at a distance of 40.12 m from the neutron target. For the natural chromium experiment, a 2.54-cm-diameter disk was used in flight path 6 with a thickness of 0.64 cm. The chromium disk was placed in the beam at a distance of 38.412 m from the neutron target. For ^{53}Cr, an enriched sample of chromium oxide was used on flight path 7. It consisted of two 2.54- by 2.54-cm samples with a thickness of 0.0122 at/b.

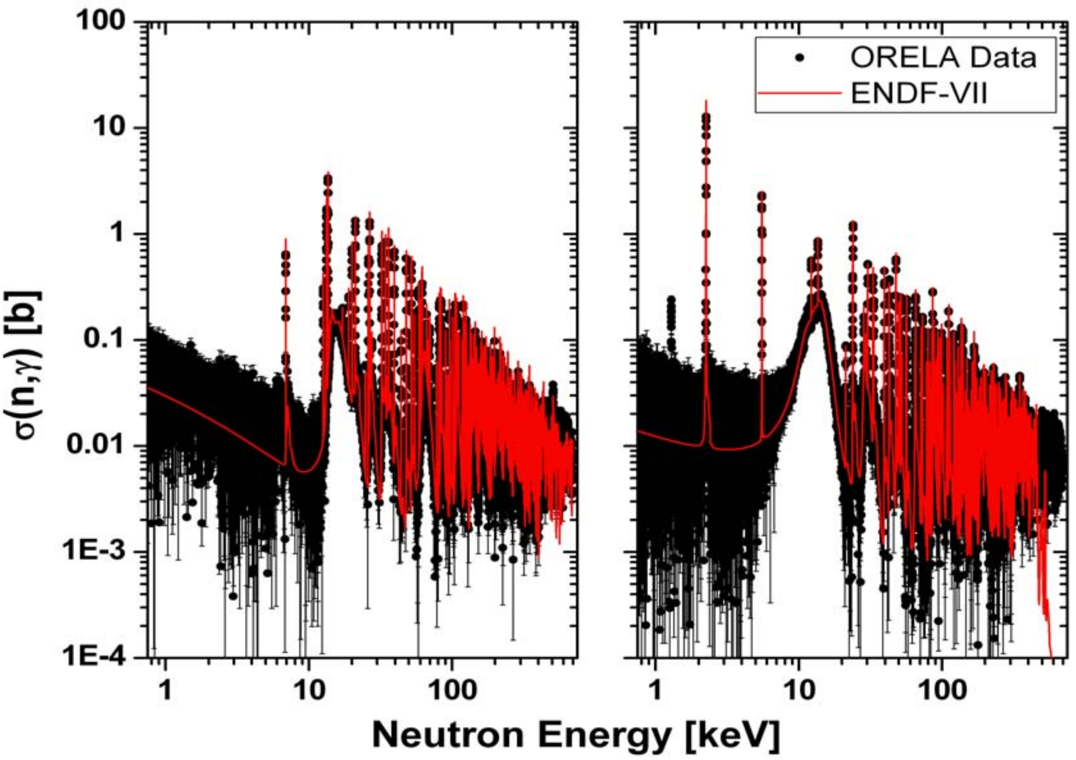

Figure 1: Neutron-capture cross section of ^{58}Ni (left) and ^{60}Ni (right) compared to ENDF-VII cross section calculated from the resonance parameters using SAMMY.

Normalization of the capture efficiency was carried out in a separate measurement using the “saturated resonance” technique by means of the 4.9-eV resonance from a gold sample [6]. A 0.5-mm-thick ^{6}Li-glass scintillator placed in the beam approximately 1 m in front of the capture sample was used to monitor the neutron flux.

2.2 Transmission measurements

High-resolution transmission experiments for determining the total cross section are not only indispensable for an evaluation but also a necessity for the analysis of neutron-capture cross sections, in order to apply corrections for experimental effects. Therefore, we made corresponding total cross-section measurements when needed. This helps to complete the resonance parameter set since some resonances with small radiation widths are not visible in the (n,γ) data and vice versa. Since high-resolution transmission data for the chromium and nickel isotopes are available from previous ORELA experiments, we made transmission measurements only for chromium in the low-neutron-energy range where no previously high-quality data are available. For the natural chromium transmission experiment, we used two metallic disks which were 0.0531 and 0.02627 atom/barn thick. These samples were mounted on a computer-controlled sample changer at a distance of 10 m from the neutron target. A pre-sample collimation limited the beam size to about a 2.54-cm diameter on the samples and allowed only neutrons from the water moderator part of the neutron source to be used. The neutron detector was an 11.1-cm-diameter, 1.25-cm-thick ^{6}Li-glass scintillator positioned in the beam at 79.815 m from the neutron source. The scintillator was viewed on edge by two 12.7-cm-diameter photomultipliers that were placed outside the neutron beam to decrease backgrounds. Additional measurements with a thick polyethylene sample were used to determine the gamma-ray background from the neutron source. To determine the overlap from low-energy neutrons from the preceding pulse, low-repetition-rate runs were made. Measurements with a thick bismuth sample were used for background checks.

3. Results

The results of our new capture and transmission experiments show differences compared to the evaluated nuclear data for ^{58}Ni, ^{60}Ni, and natural chromium obtained from the ENDF/B-VII or JENDL-3.3 nuclear data libraries. In Fig. 1 we show the neutron capture cross section for both nickel isotopes in the neutron energy range from 1 to 600 keV compared to the cross section calculated using the most recent resonance parameter set from the ENDF/B-VII library. SAMMY [7] was used to calculate the neutron-capture cross section including all experimental effects. Together with the high-resolution transmission data, good data sets are now available for new evaluations. The data are analyzed with the R-matrix code SAMMY. The Maxwellian average cross sections are calculated from the resonance parameter set. Preliminary results for ^{60}Ni are compiled in Table 1 and the calculated reaction rate is shown in Fig. 2. The analysis of our data indicated that the Maxwellian average cross section for ^{60}Ni is lower compared to previous evaluations [8, 9].

Table 1: Preliminary Maxwellian average cross section for ^{60}Ni.

kT[keV]	5	8	10	15	20	25	30	50	70	100
<σ>[mb]	61.4	57.8	52.5	41.1	33.5	28.6	25.2	18.26	15.2	12.6

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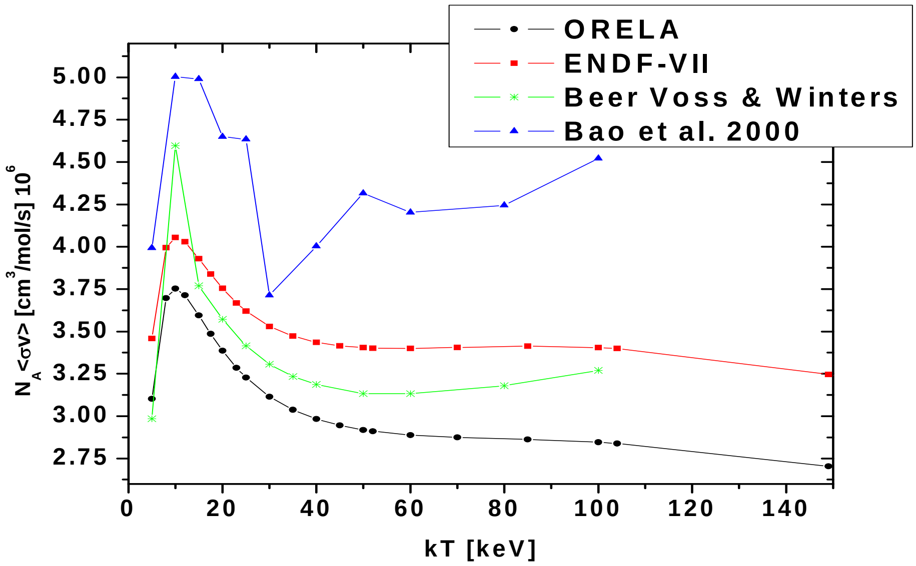

Figure 2: Comparison of our preliminary reaction rate for ^{60}Ni with evaluations [8,9].

4. Acknowledgment

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