Neutron Cross Sections Measurements for Light Elements at ORELA and their Application in Nuclear Criticality

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The Oak Ridge Electron Linear Accelerator (ORELA) was used to measure neutron total and capture cross sections of aluminium, natural chlorine and silicon in the energy range from 100 eV to ~600 keV. ORELA is the only high power white neutron source with excellent time resolution and ideally suited for these experiments still operating in the USA. These measurements were carried out to support the Nuclear Criticality Predictability Program. Concerns about the use of existing cross section data in the nuclear criticality calculations using Monte Carlo codes and benchmarks have been a prime motivator for the new cross section measurements. More accurate nuclear data are not only needed for these calculations but also serve as input parameters for *s*-process stellar models.

Keywords: neutron cross section, aluminium, silicon, chlorine, ORELA

I. Introduction

To support the Nuclear Criticality Safety Program, neutron cross section measurements have been initiated at the Oak Ridge Electron Linear Accelerator (ORELA). This will not only help to resolve inconsistencies between different data sets but will also improve the representation of the cross sections since most of the available evaluated data rely only on old measurements. Usually these were done with poor experimental resolution or only over a very limited energy range which is insufficient for current applications. To clarify inconsistencies in the criticality calculations for systems including Al, Si, Cl and ^{235}U, the neutron total and capture cross sections of Al, Cl and Si in the energy range from about 100 eV to several hundred keV have been measured and evaluated. As an example to demonstrate the discrepancies we plotted the ENDF/B-VI evaluated neutron capture cross section for natural Si and our measured data in **Fig. 1**. Finally evaluated data files based on these measurements will be utilized for both criticality analyses and benchmark data testing. In the end the data will be submitted for inclusion in ENDF/B database.

II. Experimental Set Up

ORELA is the only high power white neutron source with excellent time resolution still operating in the USA and is ideally suited for these experiments. We used two extremely high purity (0.01520 a/b and 0.04573 a/b) rectangular aluminum samples for the neutron capture measurements. For the silicon capture measurements, we used a high purity natural silicon metal sample with a thickness of 0.07831 a/b. The neutron capture of chlorine was measured using a LiCl sample with 0.09812 at/b. The samples and the C_6D_6 detectors were located at a distance of 40 meters from the neutron target. This capture system[1)] has been re-engineered to minimize the amount of structural material surrounding the sample and detectors in order to reduce the prompt neutron sensitivity. A 0.5-mm thick ^{6}Li-glass scintillator served as the neutron flux monitor. Pulse-

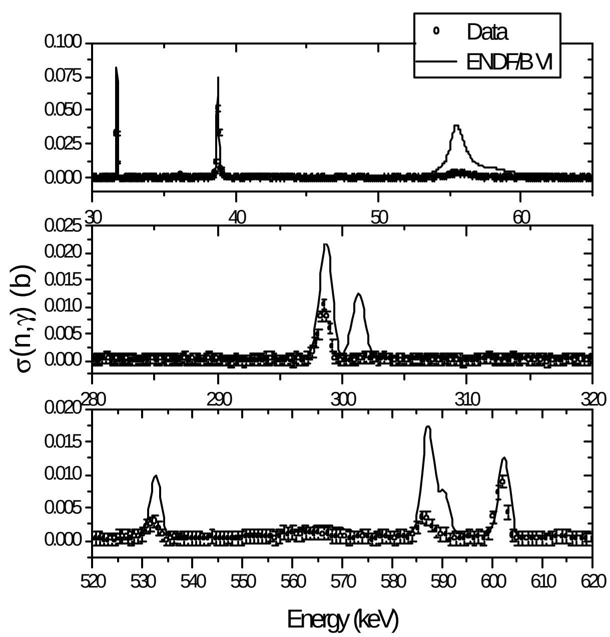

Fig. 1 Measured Si neutron capture cross section (points with error bars) compared to the latest ENDF/B VI evaluation (solid line).

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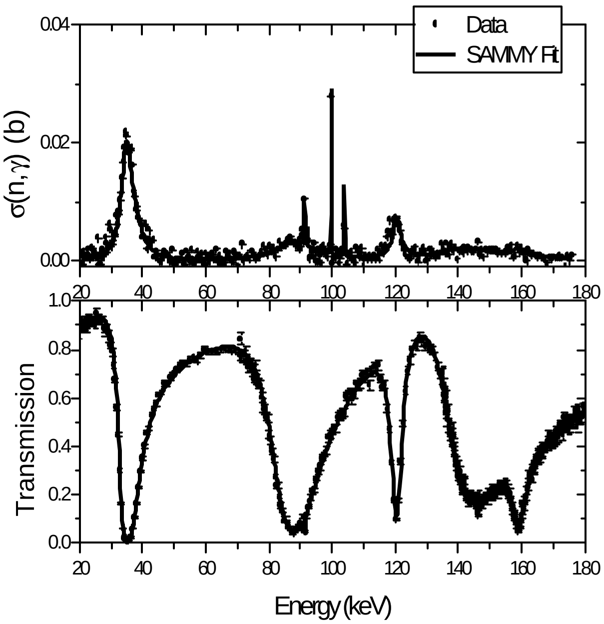

Fig. 2 Al capture and transmission data (points with error bars) and the SAMMY fit (solid line) from our measurement.

height weighting was employed with the C_6D_6 detectors; normalization of the capture efficiency was carried out in a separate measurement using the "black resonance" technique by means of the 4.9-eV resonance from a gold sample[2].

For the Al transmission measurements, the two extremely high purity (0.0189a/b and 0.1513 a/b) samples were mounted in the sample changer positioned at about 10 meters from the neutron target in the beam of ORELA. For the chlorine transmission sample we used a natural CCl_4 (thickness for chlorine 0.2075 a/b) sample as well as a "compensator" sample containing an equivalent amount of carbon (graphite disk) and sample-holder window material (brass). A pre-sample collimation limited the beam size to about 2.54-cm 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 viewed on edge by two 12.7-cm diameter photomultipliers and positioned in the beam at 79.815 meters from the neutron source. Additional measurements were made in both experiments for the open beam, and measurements with a thick polyethylene sample were used to determine the gamma-ray background from the neutron source.

III. Results

The capture and transmission data sets were analyzed with the R-matrix code SAMMY[3]. In a first step the Γ_n were determined using our new transmission measurements for Al and Cl. In the case of Si already existing transmission data sets were evaluated. To calculate accurate correction factors for experimental effects of the neutron capture data, reliable neutron widths are needed since the samples are fairly large. Using these newly determined Γ_n values for Al, Cl, and Si, SAMMY calculated the corrections for self-shielding and multiple scattering to the capture data. The results of the R-matrix fit for Al and Cl compared to our experimental data are shown in **Figs. 2 to 4** From the resonance parameters of our evaluations, we calculated the average cross sections, which are compiled in **Table 1**, together with previous evaluations. We find an overall reduction of average capture cross sections. This difference is very likely the result of underestimated neutron sensitivity in the older measurements as well as an improved calculation of the weighting function.

Table 1 Average neutron capture cross sections for Cl and Al calculated at 300 K with the ORNL evaluation compared to ENDF/B-VI and JENDL-3.2.

	^{35}Cl		^{37}Cl		^{27}Al	
Energy	Orela	ENDF	Orela	ENDF	Orela	JENDL
(keV)	σ (mb)					
2.5E-5 -1	312.8	421.5	0.42	0.41	1.02	0.65
1 – 5	22.19	26.14	0.04	0.04	0.64	0.49
5 - 10	0.31	0.37	2.17	2.75	22.15	26.31
10 - 20	31.09	0.39	0.02	0.99	0.43	0.37
20 - 30	8.59	7.70	0.68	0.59	1.31	1.02
30 - 40	0.53	0.52	0.08	0.01	11.30	10.00
40 - 50	4.93	5.77	0.33	0.42	0.95	0.77
50 – 60	5.98	7.34	0.36	0.19	0.34	0.32
60 - 70	2.52	3.00	0.18	0.32	0.38	0.37
70 - 80	0.34	0.47	0.001	0.0002	0.90	0.78
80 - 90	0.03	0.01	0.05	0.08	2.99	2.76
90 - 100	3.70	1.52	0.18	0.13	3.16	1.70
100 - 150	2.69	3.16	0.07	0.10	2.02	2.93
150 - 200	1.88	3.36	0.19	0.03	0.74	1.04
200 - 250	1.83	1.81	0.14		0.91	0.88
250 - 300	1.40		0.25		0.99	0.78
300 - 350	1.23		0.05		0.38	0.62
350 - 400	0.77		0.04		0.79	2.24
400 - 450	0.61		0.11		0.46	2.47
450 - 500	1.38		0.02		0.22	1.50

With the help of previous measurements on enriched chlorine isotopes[4] as well as the fitting code SAMMY we were able to identify the several new resonances and assign them to the individual chlorine isotopes. In addition we found several wrong spin and neutron energy assignments in the ENDF/B-VI evaluation, since we could not fit them to our data. The resonance parameters will be reported in a forthcoming publication.

For analysis of the silicon capture data, we used as starting points the Γ_n values from the latest ENDF/B-VI evaluation of the cross section for the different isotopes[5]. These transmission data sets were re-evaluated together with the new neutron capture measurements performed at ORELA. From the resonance parameters resulting from our SAMMY analysis, we calculated the average neutron capture cross sections for the different isotopes. The results are compiled the **Table 2** and compared with the most recent evaluation[5]. We find significant changes in the capture cross sections compared to ENDF/B-VI, which was based only on one experiment[6] and re-evaluations of that experiment. Once again, differences between our new data and the old data are very likely due to the underestimation of the neutron sensitivity of the old data.

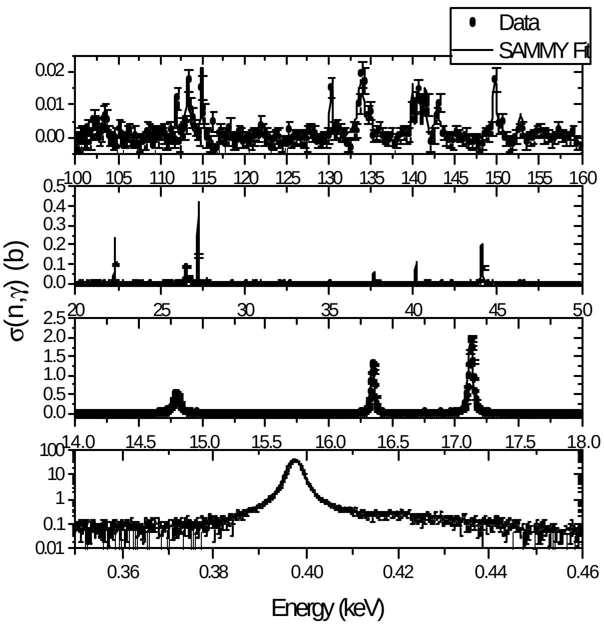

Fig. 3 Neutron capture cross section for Cl (points with error bars) and R-matrix fit to the data (solid line). For better visibility not all data point are plotted.

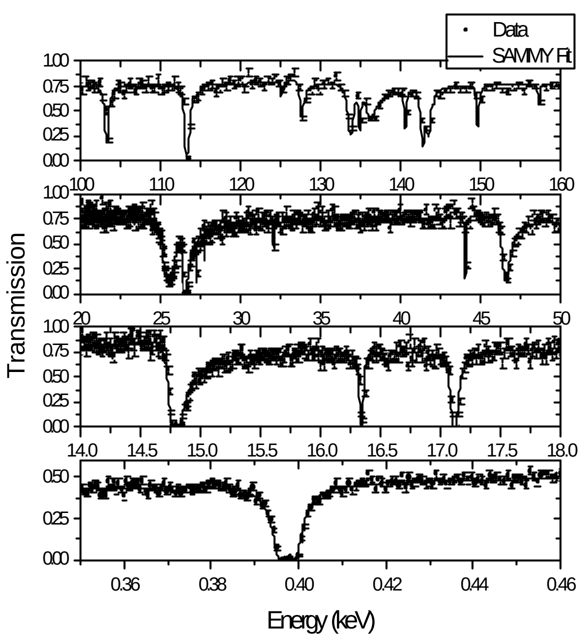

Fig. 4 Transmission of Cl (points with error bars) and R-matrix fit to the data (solid line). For better visibility not all data point are plotted.

Table 2 Average neutron capture cross sections for the Si isotopes calculated at 300K with the ORNL evaluation compared to ENDF/B-VI.

	^{28}Si		^{29}Si		^{30}Si	
Energy	Orela	ENDF	Orela	ENDF	Orela	ENDF
(keV)	σ (mb)					
2.5E-5 -1	9.95	9.81	7.05	6.96	6.28	6.25
1 – 5	0.48	0.53	0.38	0.38	42.5	343.9
5 - 10	0.25	0.33	0.23	0.23	0.55	1.06
10 - 20	0.17	0.24	22.1	30.51	2.85	0.15
20 - 30	0.10	0.21	0.15	0.15	0.11	0.11
30 - 40	0.61	0.84	30.8	32.51	0.10	0.10
40 - 50	0.10	0.32	0.44	0.41	0.09	0.09
50 – 60	1.37	12.05	0.10	0.10	0.09	0.08
60 - 70	7.94	16.90	0.08	0.08	0.08	0.08
70 - 80	0.29	0.72	0.07	0.07	0.09	0.08
80 - 90	1.79	5.69	0.07	0.07	0.09	0.08
90 - 100	0.11	0.20	0.06	0.06	0.09	0.08
100 - 150	0.31	0.37	0.07	0.07	0.17	0.13
150 - 200	1.31	1.69	2.09	1.34	3.64	2.49
200 - 250	0.29	0.38	0.05	0.05	0.97	0.75
250 - 300	0.40	0.76	0.06	0.05	0.05	0.05
300 - 350	0.02	0.33	0.33	0.23	0.23	0.23
350 - 400	0.49	0.74	1.33	0.06	0.02	0.02
400 - 450	0.01	0.04	0.15	0.16	0.13	0.14
450 - 500	0.01	0.04	0.31	0.06	0.01	0.01
500 - 550	0.29	0.92	0.19	0.20	0.01	0.01
550 - 600	0.66	2.36	0.80	1.19	0.01	0.01
600 - 650	0.69	1.64	0.93	1.13	0.10	0.22
650 - 700	0.02	0.06	0.38	0.55	0.01	0.02

IV. Conclusion

These new data and evaluations for Cl, Al and Si will help to clarify inconsistencies in benchmark calculations using MCNP. For example our new Si evaluation yields a better description of the BFS-79/5 benchmark for which the neutron spectrum is shifted to the epithermal region[7].

Acknowledgements

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References

1) R. L. Macklin and B. J. Allen, *Nucl. Instrum. Methods*, **91**, 565 (1971).
2) R. L. Macklin, J. Halperin, and R. R. Winters, *Nucl. Instrum. Methods*, **164**, 213 (1979).
3) N.M. Larson, Oak Ridge National Laboratory technical report No. ORNL/TM-9179/R5, 2000
4) R. L. Macklin, *Phys. Rev C* **29**, 1996 (1984).
5) D.M. Hetrick, D.C. Larson, N.M. Larson, L.C. Leal, and S.J. Epperson, Oak Ridge National Laboratory technical report No. ORNL/TM-11825, 1997
6) J.W. Boldeman, B.J. Allen, A.R. de L. Musgrove, and R.L. Macklin, *Nucl. Phys.* **A252** (1975) 62.

7) L.C. Leal, H. Derrien, N.M. Larson, K.H. Guber, T.E. Valentine, and R.O. Sayer, Nuclear Data Measurements, Analysis and Evaluation at the Oak Ridge National Laboratory in Support of Nuclear Criticality Safety, contribution to this conference, Abstract No. 902.