New Maxwellian Average Neutron Capture Cross Sections for ^{35,37}Cl

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The Oak Ridge Electron Linear Accelerator (ORELA) was used to measure neutron total and capture cross sections of natural chlorine in the energy range from 100 eV to 600 keV. We performed a R-matrix analysis of our new capture and transmission data up to 500 keV. From these resonance parameters new (n,γ) astrophysical reaction rates were determined over the entire energy range needed by the latest stellar models of the s process.

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In the data libraries such as ENDF/B-VI [1] or JENDL-3.2 [2] most of the older neutron induced cross section data show deficiencies or do not cover the neutron energy range which currently is important for a wide variety of applications. Many of the older measurements suffered from poor time-of-flight (TOF) resolution, and because of computer storage limitations the description of some data in the neutron energy range above several tens of keV is crude. Consequently, the number of data points may not describe the resonances accurately enough in order to apply certain corrections, such as self-shielding, multiple-scattering or Doppler broadening of individual resonances. This impacts not only the resolved cross section region but also the unresolved region, and could lead to problems in the correct processing of data from data libraries and eventually to erroneous Maxwellian average cross sections (MACS). These cross sections are input parameters for Asymptotic Giant Branch stellar models which describe the synthesis of the elements via a chain of neutron capture reactions and beta decays called the s process.

In the case of chlorine, the total cross section data below 200 keV used in the evaluated nuclear data files rely only on low resolution transmission measurements [3, 4]. Even though there exist high-resolution transmission measurements [5] for chlorine, they do not cover the neutron energy range below 500 keV, which is important for the calculation of the MACS needed by the stellar models. There exists only one high-resolution neutron capture measurement for Cl [6] performed at ORELA, using a natural chlorine and an enriched sample for ^{37}Cl. But this experiment had a low energy cut-off at 4 keV, and the analyzed resonance region up to 220 keV was covered only for ^{35}Cl. In the case of ^{37}Cl the analysis stopped at 150 keV. An important drawback of this capture experiment was the lack of high precision total cross section measurements. Since the (n,γ) measurements are usually performed with rather thick samples, as was the case in Ref. [6], corrections in the resonance analysis have to be applied for self-shielding and multiple-scattering. This require high-resolution transmission data and accurate neutron widths, and the analysis performed by Ref. [6] used the Γ_n from the low resolution transmission experiment of Ref.[4]. Therefore we made new transmission

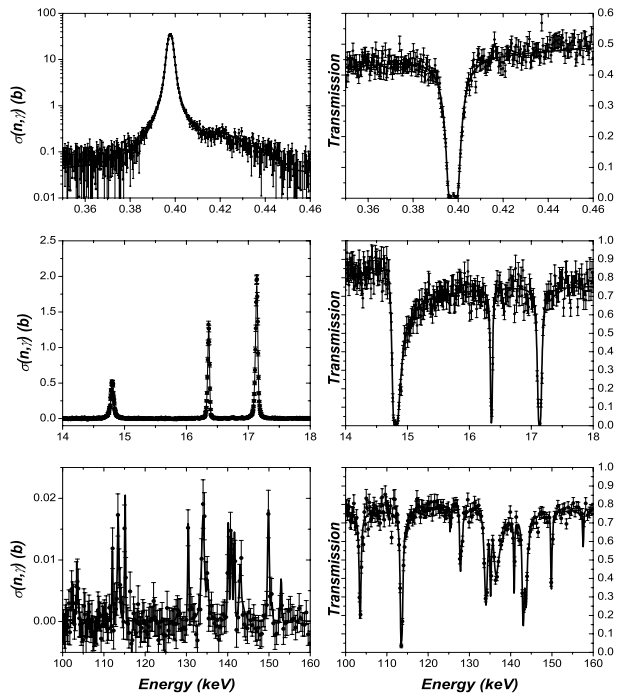

FIG. 1: Representative data (points with error bars) and SAMMY fits (solid curves) from our capture data and the corresponding transmission data for natural chlorine. The correction due to the experimental effects, like the thick sample multiple scattering correction for the 398 eV resonance in ^{35}Cl, is included by the code SAMMY. Hence the fits represent the cross sections after adjustments for the sample-dependent effects, as calculated from the resonance parameters.

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and neutron capture measurements for chlorine.

The experiments were performed using ORELA [7], which is a high intensity white neutron source with excellent timing resolution in the keV neutron energy range. Over the past thirty years ORELA has served as an excellent neutron source for many cross-section experiments. The neutron energy was determined using the TOF-technique. ORELA operated with a repetition rate of 525 Hz, 8-ns pulse width, and an average power of 7 kW. For the transmission experiment we used a natural CCl_4 sample of 77.07 g in a holder with 2.54-cm inner diameter, and a sample thickness of 0.20747 atoms/b of chlorine. By using a carbon disk in the open beam of the same amount of carbon as in the CCl_4 sample, the effect of the carbon in the sample was compensated. The chlorine transmission measurements were made using flight path no. 1. At a distance of about 9 meters from the neutron production target, the CCl_4 sample, the carbon disk, and a thick Bi sample were mounted in the computer controlled sample changer. A pre-sample collimation limited the beam size to 2.22 cm on the samples and allowed only neutrons from the water moderator part of the neutron source to be used. A ^{6}Li-loaded glass scintillation detector was positioned into the beam at the 80-meter flight station at a distance of 79.827 meters from the neutron source. The measurements were made using different filters in the beam under different experimental conditions. This measurement covered the energy range from 50 eV to 700 keV. A ^{10}B overlap filter was used to remove overlap neutrons from the preceding ORELA pulses, and a Pb filter was used to reduce the effect of the γ-flash. For all runs additional measurements were made using a polyethylene filter to measure the backgrounds mainly of γ-rays from the neutron producing target and constant room background. The black resonances in the run with a Bi sample were used to determine additional background corrections.

For the neutron capture experiment we used two 2.54 by 2.54 cm samples pressed from natural LiCl powder. These were mounted in the sample holder, so that they formed a 2.54 by 5.08 cm sample corresponding to the neutron beam size with a thickness of 0.00981 atoms/b. The measurements were performed using the pulse-height-weighting technique[8] with a pair of C_6D_6 scintillation detectors located on flight path no. 7 at a distance of 40.12 m from the neutron target. To determine the energy dependent neutron flux, a 0.5 mm thick ^{6}Li-loaded glass scintillation detector was placed in the beam at a distance of 43 cm in front of the sample. The absolute normalization of the capture measurements was made by applying the saturated resonance technique [9], using the 4.9-eV resonance in gold. Measurements with no sample and with a carbon sample were used to subtract the smoothly varying backgrounds. Over the past years this capture system [8] has undergone major changes. As described in Ref. [10] the massive Al sample changer and beam pipe were replaced by a carbon fiber tube with much less mass. Also the C_6F_6 scintillation detectors were replaced by the less neutron sensitive C_6D_6 detectors having fewer enclosures. This resulted in significantly reduced sensitivity to sample scattered neutrons [11]. These changes have also contributed to a simplification and improved reliability of the calculation of the pulse-height weighting function. As demonstrated in case of the (n,γ) cross section measurements for ^{88}Sr, ^{136}Ba, ^{142}Nd, and the silicon isotopes [10–13], the experimental apparatus is now well suited for measuring small cross sections, as it is also the case for the chlorine isotopes. ORELA was operated under the same conditions as for the transmission experiment. The capture measurements were also made with a ^{10}B overlap filter and a Pb filter to reduce the γ-flash; these filters were placed at a distance of 5 m from the neutron target.

Our new transmission and capture data were analyzed in the resolved resonance region using the multilevel R-matrix code SAMMY [14]. For ^{35}Cl, the *(n,p)* channel is open, therefore the *(n,p)* data from Refs. [15] and [16] were also incorporated in the analysis. The chlorine data were fitted in the energy range from 0.0253 eV to 500 keV, where we obtained resonance parameters for 122 and 88 resonances for ^{35}Cl, and ^{37}Cl, respectively. Because of our high resolution transmission data we resolved reported doublets into individual resonances for ^{35}Cl in the energy range analyzed by Ref. [6]. The combination of the transmission and capture data led to 12 new resonance assignments for ^{37}Cl in the energy range up to 150 keV. Above 220 keV we observed 64 resonances for ^{35}Cl which had not been previously reported. In addition above 150 keV we assigned 64 new resonances to ^{37}Cl. Representative data and SAMMY fits for our capture and transmission data are shown in Fig. 1.

As for many elements with very small (n,γ) cross sections, the direct capture (DC) component can contribute a significant amount to the reaction rates. We performed the DC calculations using the code TEDCA [17, 18], which can take into account E1, M1, and E2 transitions. The number of open parameters is considerably reduced by employing folding potentials for the optical potentials in the entrance channel and for the bound state [19]. At low energies, a real optical potential can be used for the projectile-target system provided that no other reaction channels are open or have almost no influence as is the case for ^{35}Cl. The potential shape and depth are obtained by folding a density-dependent effective nucleon-nucleon interaction [20] with a nuclear density distribution (for details see, e.g., Ref. [19]). For nucleons, the density distribution is usually found by assuming a δ-function. The target density distribution is taken from electron-scattering data [21]. The only open parameter λ in the folding potentials can be determined by the requirement of reproducing certain nuclear properties. For the bound state potentials this is the requirement to reproduce the binding energy. The λ parameter for the potential in the entrance channel is determined by reproducing experimental potential scattering lengths or elastic scattering cross sections. Thus, all parameters are

TABLE I: Maxwellian Averaged Cross Sections for the Cl isotopes compared to the most recent evaluation. The resonance and direct capture (DC) values are listed in separate columns as well as their corresponding uncertainties. The total Maxwellian average cross sections for each isotope are reported in column 4 and 8 respectively.

kT	^{35}Cl				^{37}Cl			
	Resonance	DC	Resonance + DC.	Ref.[26]	Resonance	DC	Resonance + DC	Ref.[26]
(keV)			(mb)				(mb)	
2	52.32 ± 1.57	0.57 ± 0.17	52.88 ± 1.58		2.64 ± 0.11	1.10 ± 0.57	3.74 ± 0.58	
5	27.29 ± 0.82	0.37 ± 0.11	27.66 ± 0.83	26.00	4.84 ± 0.19	0.69 ± 0.36	5.54 ± 0.41	6.95
8	23.56 ± 0.71	0.30 ± 0.09	23.86 ± 0.71	24.10	4.05 ± 0.16	0.55 ± 0.29	4.59 ± 0.33	5.67
10	21.27 ± 0.64	0.28 ± 0.08	21.55 ± 0.64	22.30	3.58 ± 0.14	0.49 ± 0.26	4.06 ± 0.29	4.94
15	16.42 ± 0.49	0.26 ± 0.08	16.68 ± 0.50	17.60	2.77 ± 0.11	0.40 ± 0.21	3.17 ± 0.24	3.72
20	13.06 ± 0.39	0.25 ± 0.08	13.31 ± 0.40	14.10	2.27 ± 0.09	0.35 ± 0.18	2.61 ± 0.20	2.99
23	11.57 ± 0.35	0.25 ± 0.08	11.83 ± 0.36		2.05 ± 0.08	0.32 ± 0.17	2.37 ± 0.19	
25	10.75 ± 0.32	0.26 ± 0.08	11.01 ± 0.33	11.70	1.93 ± 0.08	0.31 ± 0.16	2.24 ± 0.18	2.50
30	9.12 ± 0.27	0.27 ± 0.08	9.39 ± 0.29	10.00	1.70 ± 0.07	0.28 ± 0.15	1.98 ± 0.16	2.15
35	7.93 ± 0.24	0.29 ± 0.09	8.22 ± 0.25	8.78	1.53 ± 0.06	0.26 ± 0.14	1.79 ± 0.15	1.87
40	7.03 ± 0.21	0.31 ± 0.09	7.34 ± 0.23	7.90	1.41 ± 0.06	0.25 ± 0.13	1.66 ± 0.14	1.66
45	6.32 ± 0.19	0.34 ± 0.10	6.66 ± 0.22	7.17	1.32 ± 0.05	0.23 ± 0.12	1.56 ± 0.13	1.48
50	5.76 ± 0.17	0.37 ± 0.11	6.13 ± 0.21	6.60	1.26 ± 0.05	0.22 ± 0.11	1.48 ± 0.13	1.34
60	4.92 ± 0.15	0.43 ± 0.13	5.36 ± 0.20	5.80	1.17 ± 0.05	0.20 ± 0.11	1.37 ± 0.11	1.12
70	4.33 ± 0.13	0.51 ± 0.15	4.83 ± 0.20	5.20	1.10 ± 0.04	0.19 ± 0.10	1.29 ± 0.11	0.96
85	3.68 ± 0.11	0.63 ± 0.19	4.32 ± 0.22	4.55	1.03 ± 0.04	0.17 ± 0.09	1.20 ± 0.10	0.78
100	3.22 ± 0.10	0.77 ± 0.23	3.99 ± 0.25	4.07	0.96 ± 0.04	0.16 ± 0.08	1.12 ± 0.09	0.65

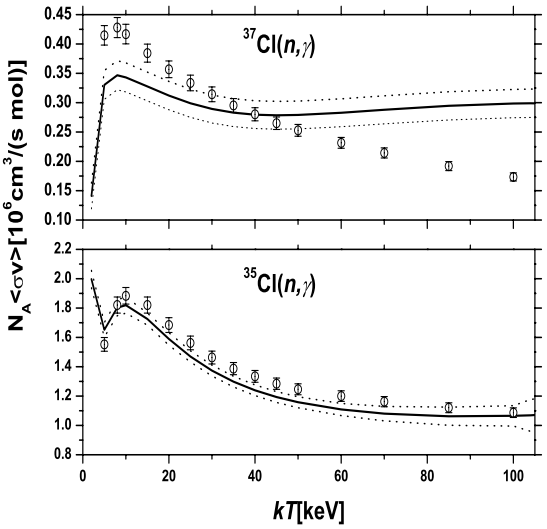

FIG. 2: Astrophysical reaction rates for the ^{35,37}Cl(n, γ) reaction calculated from the cross sections of the present work (solid curves, with the dashed curves depicting the uncertainties), and Ref.[26](∘).

determined without making use of any reaction data. In our calculation for direct neutron capture on ^{35}Cl and ^{37}Cl we use the potential radii given in Ref. [22] to determine λ. The measured scattering lengths (especially in the case of ^{35}Cl) contain resonant contributions [22] and can therefore not be used straightforwardly for the optical potential of the DC calculation. Thus, a comparison of our DC result to the thermal cross section cannot be done without adding the appropriate resonance terms. Transitions to the ground state and several excited states in the final nucleus have been summed to obtain the total cross section. The nuclear properties (excitation energy, spin, parity, spectroscopic factor) of the final states in ^{36}Cl were taken from Ref. [23], whereas for those of ^{38}Cl the more recent data of Ref. [24] was combined with those of Ref. [23]. The resulting cross sections have been parameterized into s-, p- and d-wave capture cross sections. The quoted errors arise mainly from the uncertainty in the experimental scattering radii. An additional error factor has been introduced to account for the uncertainties inherent in the spectroscopic factors.

According to our calculations the DC component of ^{37}Cl can account for most of the thermal cross section, therefore the parameters of the external levels in the R-matrix responsible for a large part of the remainder of the thermal cross sections had to be adjusted in a way that they describe the "DC-corrected" contribution to the thermal value. The adjustment of the parameters of these external levels in turn required adjustments in the parameters of some of the other resonances. On the other hand, the large thermal capture cross section of ^{35}Cl did not require any adjustment for the DC at thermal energies. The effect of the DC contribution to the capture cross section of ^{35}Cl at lower kT is small and within the quoted experimental errors. Whereas for ^{37}Cl the DC contribution can account for as much as 20% of the Maxwellian average capture cross section and is therefore not negligible.

We calculated the astrophysical ^{35,37}Cl(n,γ) rates due to our resonance parameters using standard techniques [25]. To this, the DC contributions have to be added in order to obtain the total Maxwellian average cross section rates. Our new rates and the individual contributions are compiled in Table I and compared to the most recent evaluation. These rates were used to calculate the astrophysical reaction rates which are plotted in Fig. 2. From our new data we find a 6% lower MACS at kT=30 keV for ^{35}Cl compared to Ref. [26]. At lower kT our values cross the data from Ref. [26], and at 5 keV we calculated

a 6% higher MACS. For ^{37}Cl(n,γ) we find a reduction of the MACS of 8% for kT=30 keV and 20% for 8 keV. At higher kT our MACS is higher due to the resonance contribution above 150 keV which were not included in the latest evaluation.

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