$^{35}Cl(n,p)^{35}S$ cross section from 25 meV to 100 keV

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We have measured the $^{35}Cl(n,p)^{35}S$ cross section from 25 meV to 100 keV. Strengths were determined for the resonances at $E_n = 398$, 4249, 16 340, 27 316, and 57 700 eV. The proton width for the $J^\pi = 2^+$ state just below threshold was calculated using previously known resonance parameters and the thermal cross section. The cross section calculated from the parameters for this state was found to be in good agreement with our data to approximately 100 eV. The astrophysical reaction rate, $N_A\langle\sigma v\rangle$, was calculated from the resonance strengths determined in our measurements, plus the thermal cross section. The role of this reaction in the nucleosynthesis of light elements in the *s* process as well as in explosive nucleosynthesis is discussed.

Except at thermal energy, there has been only one previously published [1] measurement of the $^{35}Cl(n,p)^{35}S$ cross section for energies below a few MeV. Because those measurements were made with the relatively poor resolution of a lead-slowing-down spectrometer, and because they were limited to a maximum energy of about 8 keV, a new measurement to higher energy with better resolution was desirable. Also, the $^{35}Cl(n,p)^{35}S$ reaction plays a role in the nucleosynthesis of light elements in the *s* process [2] as well as in explosive environments [3]. A measurement of this cross section to higher energy could help to reduce the uncertainty in the nucleosynthesis calculations.

The technique used in these measurements has been described elsewhere [4], so only the salient features will be mentioned. The measurements were performed at the moderated "white" neutron source of the Manual Lujan, Jr. Neutron Scattering Center (LANSCE) [5]. The ^{35}Cl samples were made by vacuum evaporation of natural potassium chloride to a total thickness of 300 $\mu g/cm^2$ onto a 8.5-μm-thick aluminum backing. The sample was 1.9 cm long by 0.5 cm wide. It was placed so that the longer dimension was approximately parallel to the incident neutron beam, but was inclined so that the front was 0.3 cm lower than the back. Protons were detected with a silicon surface-barrier detector which was 10 μm thick by 50 mm^2 in area. The detector was located at 90° with respect to the incident neutron beam about 1 cm above the center of the sample. The $^{35}Cl(n,p)^{35}S$ cross sections were calculated from the proton yields in the detector assuming the cross section to be isotropic. The measurements were made relative to the $^6Li(n,\alpha)t$ cross section using a separate ^6Li sample and solid-state detector as a flux monitor and were converted from yields to cross sections using the known thermal cross section for ^6Li (Ref. [6]) and ^{35}Cl (Ref. [7]), and the latest evaluation for the energy dependence of the ^6Li cross section [6]. The data were taken in two-parameter mode, pulse height (or proton energy) versus time of flight (or neutron energy). The time-of-flight channel width was 128 ns. To improve the statistical accuracy, the off-resonance data were compressed into much coarser bins. The time of flight to energy calibration was made with the aid of cobalt and uranium filters which had been placed in the neutron beam ahead of the sample position during a separate calibration run.

There has been a wide range of values reported for the thermal $^{35}Cl(n,p)^{35}S$ cross section [8]; from 169±34 to 587±15 mb. The most recent measurements have resulted in thermal cross-section values of 587±15 (Ref. [9]), 446±40 (Ref. [10]), and 489±14 mb (Ref. [7]). Earlier measurements have been summarized by Durham and Girardi [9]. We chose to normalize our measurements to the value recommended in Mughabghab, Divadeenam, and Holden [8], 489±14 mb, which is identical to the value of Sims and Juhnke [7].

The $^{35}Cl(n,p)^{35}S$ cross sections resulting from our measurements are shown in Figs. 1 and 2. The representative error bars shown on our data depict the one-standard-deviation relative errors only. The relative uncertainties are dominated by counting statistics. A normalization uncertainty of 3.5% was calculated from the published uncertainties in the ^{35}Cl (Ref. [7]) and ^6Li (Ref. [6]) thermal cross sections.

Also shown in Figs. 1 and 2 are the data of Popov and Shapiro [1], which were measured with a lead-slowing-

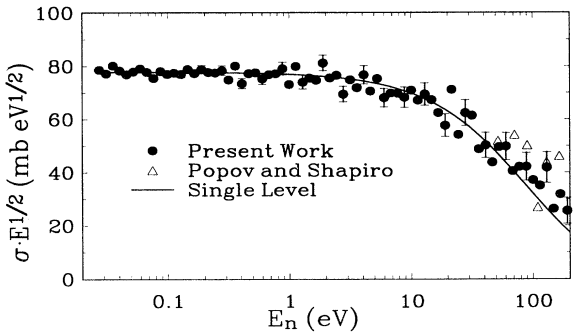

FIG. 1. $^{35}Cl(n,p)^{35}S$ reduced cross section from thermal energy to 200 eV. Our data are shown as solid circles whereas those of Popov and Shapiro [1] are shown as open triangles. The solid curve is from a single-level Briet-Wigner calculation as explained in the text.

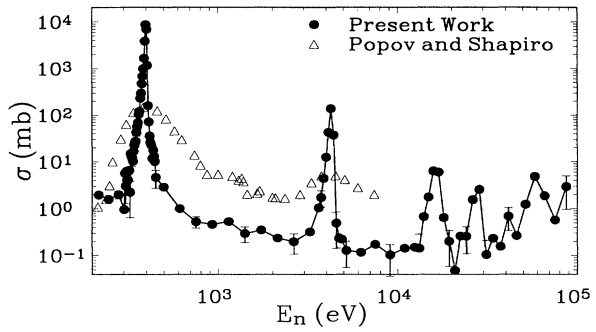

FIG. 2. ^{35}Cl(n,p)^{35}S cross section from 200 eV to 100 keV. Our data are shown as solid circles whereas those of Popov and Shapiro [1] are shown as open triangles.

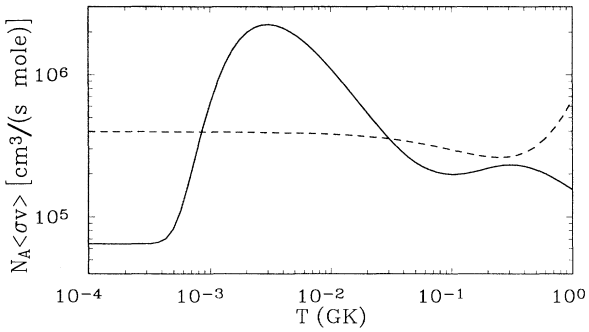

FIG. 3. Reactivity versus temperature for the ^{35}Cl(n,p)^{35}S reaction. The solid curve is the total reactivity from the sum of the resonance strengths we observed plus a $1/v$ component normalized to the thermal cross section, whereas the dashed curve is from the theoretical calculations of Woosley *et al.* [16].

down spectrometer. We renormalized these previous data (by a factor of 2.57) to account for the difference in the previously recommended thermal cross section [11] (which was used by Popov and Shaprio to normalize their yields to cross sections), compared to the presently recommended value [8]. Below 200 eV the two sets of data agree within the experimental errors. Above this energy the main difference appears to be due to the much poorer energy resolution of the previous measurement. Also, a (very narrow) resonance near 1 keV reported by Popov and Shapiro, as well as in other measurements [12,13], is not evident in our data.

The resonance energies, E_0, and strengths, $\omega\gamma = g\Gamma_n\Gamma_p/\Gamma$, determined from our data are given in Table I. The uncertainties given for our resonance energies were calculated by adding in quadrature the full width at half maximum of the LANSCE pulse (125 ns) and our time-of-flight channel width (128 ns). The resonance strengths were calculated by numerical integration over the peaks in our data. Because of our relatively poor energy resolution, shape analyses of the resonances were not performed. Also, our resolution was not good enough to resolve all the known [8] resonances above the one at 4.249 keV, so the strengths we give in Table I may represent an average over unresolved resonances in these cases.

It has been known for some time [14] that a level below threshold dominates the ^{35}Cl+n cross sections below approximately 100 eV. Using the (other) partial widths, the resonance energy, and the thermal cross section recommended by Mughabghab, Divadeenam, and Holden [8] it is possible to calculate the proton width for this resonance. The result given in Table I. The ^{35}Cl(n,p)^{35}S cross section calculated from these parameters is in good agreement with our data to approximately 100 eV as is shown in Fig. 1.

Also given in Table I are the strengths, calculated by us from the partial and total widths determined by Popov and Shapiro [1], as well as the strengths we calculated from the parameters recommended in the compilation of Mughabghab, Divadeenam, and Holden [8]. Because the presently accepted thermal cross section is 2.6 times

TABLE I. ^{35}Cl(n,p)^{35}S resonance parameters.

E_0 (keV)		$\omega\gamma$ (eV)		
Mughabghab *et al.* [8]	Present work	Mughabghab *et al.* [8]	Present work	Popov and Shapiro [1]
−0.180±0.03[a]		2.4×10^{-3}	6.2×10^{-3}	$(2.4\pm0.8)\times10^{-3}$
0.398±0.001	0.398±0.006	7.9×10^{-3} [b]	1.0×10^{-2}	$(2.8\pm0.9)\times10^{-3}$ [b]
4.249±0.002	4.25±0.20	1.6×10^{-2} [c]	3.5×10^{-2}	$(9.8\pm5.2)\times10^{-3}$ [d]
16.340±0.005	16.3±1.5		6.4×10^{-2}	
27.316±0.025	27.3±3.2		6.9×10^{-2}	
57.70±0.08	58.1±9.9		0.86	

[a]For the −0.18 keV resonance, the values given under "$\omega\gamma$" are actually the proton widths Γ_p. The proton width given under present work was calculated from the (other) resonance parameters and the thermal cross section in Mughabghab, Divadeenam, and Holden [8] and was used to calculate the curve in Fig. 1.

[b]Using $J=2$ for this resonance.

[c]Assuming $J=1$ as suggested by Morgenstern *et al.* [12].

[d]Average of the strengths calculated from the widths given for $J=2$ and $J=3$. For $J=1$, only limits were given for $g\Gamma_n$ and Γ.

larger than the value used by Popov and Shapiro, it is to be expected that their strengths should be smaller than ours by this factor. From Table I it appears that when this factor of 2.6 is taken into account, the strengths determined from the parameters of Popov and Shapiro are systematically lower than ours, whereas those calculated from the parameters of Mughabghab, Divadeenam, and Holden are systematically higher. However, the strengths from the two experiments agree to within the experimental errors when the factor of 2.6 is taken into account. Also, the proton width of Popov and Shapiro for the negative energy resonance, when multiplied by this factor, agrees with the width we determined. However, it is not clear what fraction of the error quoted by Popov and Shapiro arises from the fairly large uncertainty associated with the thermal cross section they used. Also, we calculated the total errors on the strengths of Popov and Shapiro assuming that the errors in the individual widths are uncorrelated, which is probably not a good assumption.

Following Bahcall and Fowler [15], the astrophysical reaction rate, $N_A\langle\sigma v\rangle$, was calculated using our resonance strengths plus a term for the $1/v$ component of the cross section. The rate parameterized in this way should be directly usable in most nucleosynthesis codes. The result is

$$N_A\langle\sigma v\rangle = 6.48\times10^4 + [1.61\times10^3 e^{-(0.0045/T)} + 5.64\times10^2 e^{-(0.048/T)} + 1.03\times10^4 e^{-(0.185/T)} + 1.11\times10^4 e^{-(0.309/T)} + 1.38\times10^5 e^{-(0.651/T)}]/T^{3/2}\ \text{cm}^3/(s\ \text{mole})\ , \quad (1)$$

where T is the temperature in GK. The above parametrized rate agrees with the rate calculated from numerical integration of the data to within 20% at all temperatures except for those just below the 398 eV resonance. Better agreement could be obtained by including more parameters [15] to describe the divergence from $1/v$ in the low-energy cross section, but this is probably not worthwhile as the major difference occurs at temperatures below those used in most nucleosynthesis calculations. The rate given by Eq. (1) is shown in Fig. 3. Also shown is a theoretical estimate for the rate from Woosley *et al.* [16].

The ^{35}Cl$(n,p)^{35}$S reaction plays a role in the nucleosynthesis of the rare stable isotope ^{36}S in the *s* process. A calculation by Beer and Penzhorn [2] indicates that most, if not all, of the solar ^{36}S abundance could result from the *s* process. Unfortunately, because our measurements extend to only 100 keV, and because several broad levels in ^{36}Cl have been observed [8] at slightly higher energies in other reactions, the reaction rate determined from our data can only be considered as a lower limit for temperatures above approximately 0.3 GK. At *s*-process temperatures ($T\approx0.35$ GK) our data together with the ^{35}Cl$(n,\gamma)^{36}$Cl measurements of Macklin [17] can be used to estimate that the (n,γ) rate is approximately 6 times larger than the rate for (n,p). (The ratio at thermal energy is 88.) This agrees to within about 10% with the ratio of the theoretical rates of Woosley *et al.* [16]. Hence, both theory and experiment indicate that there may be some branching at ^{35}Cl in the *s* process. However, the relatively small size of the branch to ^{35}S, together with the short (87.5 days) half life and low capture cross section (calculated [16] to be 3.9 mb at 30 keV) of ^{35}S, makes it most likely that in the *s* process ^{36}S would be made predominantly via ^{36}Cl$(n,p)^{36}$S or ^{39}Ar$(n,\alpha)^{36}$S rather than through the sequence ^{35}Cl$(n,p)^{35}$S$(n,\gamma)^{36}$S. However, the important ^{35}S$(n,\gamma)^{36}$S, ^{36}Cl$(n,p)^{36}$S, and ^{39}Ar$(n,\alpha)^{36}$S cross sections have not been measured although preliminary data for the shape of the ^{36}Cl$(n,p)^{36}$S cross section exist [18].

In conclusion, it should also be mentioned that the explosive nucleosynthesis calculations of Howard *et al.* [3] resulted in a fairly large overproduction of ^{36}S. Hence, the *s* process is not the only means which has been suggested for producing this rare isotope. At present there are still several unmeasured reaction rates of importance in both calculations so that it is not yet possible to determine with confidence where ^{36}S originated.

Note added in proof. We thank Yu. M. Gledenov for calling to our attention a previous work [19] in which the strengths of the 398-, 1100-, and 4249-eV resonances were measured to be 10.8 ± 1.6, 0.2 ± 0.3, and 40 ± 8 meV, respectively, in agreement with the present work.

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