$^{36}Cl(n,p)^{36}S$ cross section from 25 meV to 800 keV and the nucleosynthesis of the rare isotope ^{36}S

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We have measured the $^{36}Cl(n,p)^{36}S$ cross section from thermal energy to approximately 800 keV. Parameters for eight resonances between 900 eV and 70 keV were determined in a multilevel fit to our data which also included information from published $^{36}S(p,\gamma)^{37}Cl$ measurements. The $^{36}Cl(n,p)^{36}S$ reaction can play a critical role in the production of the rare isotope ^{36}S in explosive nucleosynthesis and *s*-process calculations. The astrophysical rate for this reaction was calculated from our measured cross sections and was found to be significantly smaller than the theoretical rate used in previous nucleosynthesis calculations. We discuss the impact of this result on the nucleosynthesis of ^{36}S.

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I. INTRODUCTION

It has been speculated that rare isotopes are valuable diagnostics that will lead to a better understanding of the properties of the astrophysical environment in which they were produced. Most of the rare isotopes are thought to originate in explosive environments. For example, in the framework of explosive carbon burning Howard *et al.* [1] were able to synthesize most of the neutron-rich rare nuclei in the range $36 \leq A \leq 76$ approximately in their solar-system abundance ratios. The paper of Howard *et al.* has been particularly useful to experimentalists because the important reaction sequences were outlined and the cross sections of greatest impact were identified. For example, the $^{36}Cl(n,p)^{36}S$ reaction was identified as being important mainly for its influence on the production of the rare isotope ^{36}S. Subsequent studies have lead to revised estimates for the parameters describing explosive carbon burning. In particular, the neutron flux may not be as large as estimated by Howard *et al.* However, more recent calculations still appear to overproduce ^{36}S. The parameters of explosive nucleosynthesis calculations remain fairly uncertain and new processes (such as the ν process [2,3]) are invented occasionally as our knowledge evolves. So it remains important to measure cross sections affecting the production and destruction of these rare nuclei.

The *s* process has been suggested as an alternative mechanism for the production of ^{36}S. Beer and Penzhorn [4] studied the contribution of the *s* process to the abundance of nuclei near ^{40}Ar. One result of their calculation was that (mainly the weak component of) the *s* process can account for most of the observed ^{36}S abundance. However, their results for ^{36}S are fairly uncertain in part because cross sections for the reactions that lead directly to ^{36}S [i.e., $^{36}Cl(n,p)^{36}S$ and $^{39}Ar(n,\alpha)^{36}S$] had not been measured and so they had to rely on theoretical calculations for the reaction rates.

There have been four previous $^{36}Cl(n,p)^{36}S$ measurements reported, two at thermal energy [5,6] and two in the resonance region [7,8]. The two measurements of the thermal cross section differ by a factor of 9. However, the $^{36}Cl(n,p)^{36}S$ peak in the measurements of Ref. [6] apparently contained a large contribution from the $^{36}Ar(n,\alpha)^{33}S$ reaction (from the counting gas used in the ionization chamber) which was not corrected for, so this measurement is thought to be unreliable. We have reported [8] preliminary data from thermal energy to approximately 100 keV from measurements made with targets evaporated from a water solution. However, problems associated with target thickness and nonuniformity have kept us from converting the yields from these measurements to absolute cross sections. The new vacuum evaporated targets prepared for the present work have solved these problems. Finally, in Ref. [7] the strengths of three resonances between 1.3 and 8 keV were reported. Because of the limited energy range covered and because absolute cross sections as a function of energy were not given in Ref. [7] these measurements were of limited value for nucleosynthesis calculations.

To help reduce the uncertainty in the nucleosynthesis calculations, we undertook a measurement of the $^{36}Cl(n,p)^{36}S$ cross sections across the range of energies of importance to nuclear astrophysics. Also, our data, together with information from $^{36}S(p,\gamma)^{37}Cl$ measurements [9], were used in a resonance analysis to determine parameters for several resonances near the neutron threshold.

II. EXPERIMENTAL PROCEDURES

The measurements were performed at the moderated "white" neutron source of the Manuel Lujan, Jr. Neutron Scattering Center (LANSCE) [10] using an apparatus which has been described elsewhere [11] so only the salient details will be mentioned herein.

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The ^{36}Cl samples were made by vacuum evaporation of sodium chloride onto an aluminum backing 25 μm in thickness. The sample preparation procedures are described in Ref. [12]. The chlorine was enriched to about 55% in ^{36}Cl. The samples were 1 cm in diameter and during the experiments were placed so that the plane of the sample was inclined by about 2° with respect to the incident neutron beam. Most of the measurements were made with a sample containing 5.95 μCi of ^{36}Cl. Background measurements were also made with a blank aluminum backing foil.

Protons and α particles from the ^{36}Cl$(n,p)^{36}$S and $(n,\alpha)^{33}$P reactions were detected with a silicon surface-barrier detector which was 50 μm thick by 450 mm^2 in area. The detector was placed at 90° to the neutron beam at about 2.2 cm from the center of the sample. Measurements were also made with a dual-gridded ion chamber [13]. The result from the latter detector were limited to energies below a few keV because of a much poorer signal-to-background ratio at higher energies. However, measurements with the ion chamber resulted in a good separation of the alpha particles from the protons for the $E_0 = 902.6$ eV resonance as will be discussed below.

The measurements were made relative to the ^{6}Li$(n,\alpha)^3$H cross section using a separate ^{6}Li sample and solid-state detector as a flux monitor. The data were converted from yields to cross sections using the latest evaluation for the ^{6}Li cross section [14]. In previous measurements we have either measured the absolute thermal cross section in a separate experiment at a reactor or used previously measured thermal cross sections to convert our yields to absolute cross sections. Due to the small size of the ^{36}Cl$(n,p)^{36}$S thermal cross section, our attempted measurements at reactors have so far not been successful. Also, we were not aware of the thermal cross-section measurement of Ref. [5] until after our measurements were completed. Hence, in the present case the absolute normalization was made during the LANSCE experiments. The absolute LANSCE flux was measured using the same method reported in Ref. [15]. In this technique, a calibrated ^{241}Am source was used to measure the detector solid angles, and a calibrated ^{6}Li sample was used to measure the absolute flux. In addition, the number of ^{36}Cl nuclei in the sample was determined relative to a standard ^{36}Cl source using a high-purity germanium detector. Unfortunately, the ^{36}Cl and ^{6}Li samples did not have the same diameter and the ^{36}Cl sample was larger than the central uniform part of the beam spot from our collimator. We used the Monte Carlo technique to calculate that correcting for these effects leads to a 35% increase in the size of the cross section. We also used the Monte Carlo technique to estimate that the uncertainty in this correction due to possible misalignments of the targets with the neutron beam is less than 5%. The ^{36}Cl$(n,p)^{36}$S data were also corrected for the anisotropy in the cross section of the ^{6}Li$(n,\alpha)^3$H flux monitor as discussed in Ref. [16]. Also, we assumed that the ^{36}Cl$(n,p)^{36}$S cross section was isotropic when converting our measured yields to cross sections. This assumption may not be valid at all energies because at least some of the resonances appear to be p wave as will be discussed below.

The data were taken at a source-to-sample distance of 7.02 m with a time-of-flight channel width of 16 ns. For energies above approximately 800 eV this channel width was retained in the analysis to obtain the best possible resolution. Below 800 eV, where no resonances were observed, the data were compressed into 50 bins, equally spaced on a logarithmic scale in neutron energy, to improve the statistical accuracy. The time-of-flight to energy calibration was made with the aid of a uranium filter which had been placed in the neutron beam ahead of the sample position during a separate calibration run. Dips in the time-of-flight spectrum due to aluminum and manganese in the mercury shutter windows were also used in the calibration.

Pulse-height versus time-of-flight spectra are shown in Figs. 1 and 2. The data in these figures represent about one-quarter of the total data taken. In Fig. 1 the time-of-flight region near thermal neutron energy is shown. At these energies where the cross section has a $1/v$ shape ^{10}B in the sample and the detector accounted for about a 16% background [mainly from the ^{10}B(n,α_0) reaction which results in a peak at nearly the same energy as that from the ^{36}Cl$(n,p)^{36}$S reaction]. Measurements with a blank aluminum foil indicated that about one-half of this background was due to ^{10}B in the ^{36}Cl sample. We corrected for this background by using the measured shape and size of the ^{10}B(n,α_1) peak, and the $(n,\alpha_0)/(n,\alpha_1)$ ratio from the latest evaluation [14] to subtract the contribution of the ^{10}B(n,α_0) group from the ^{36}Cl$(n,p)^{36}$S peak.

In Fig. 2 the time-of-flight region from about 800 eV to roughly 2 MeV is shown. At these energies background

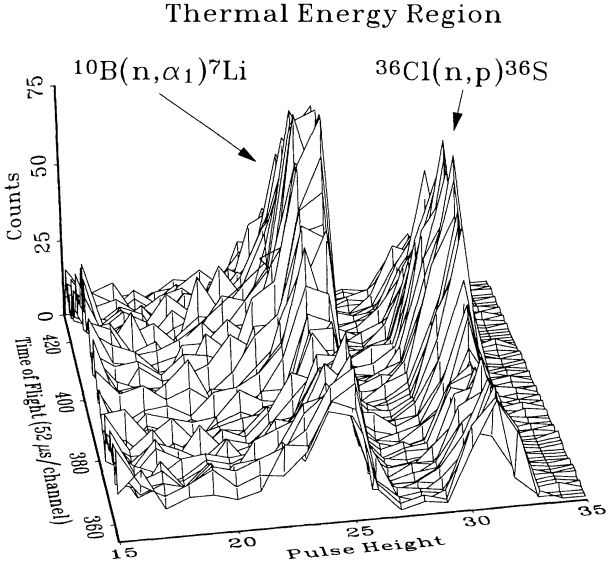

FIG. 1. Pulse-height vs time-of-flight spectra for the region near thermal neutron energy. The peaks due to the ^{36}Cl$(n,p)^{36}$S and ^{10}B$(n,\alpha_1)^7$Li reactions are indicated. Alpha particles from the ^{10}B$(n,\alpha_0)^7$Li reaction were not resolved from the ^{36}Cl$(n,p)^{36}$S peak and cause about a 16% background at these energies. See the text for details.

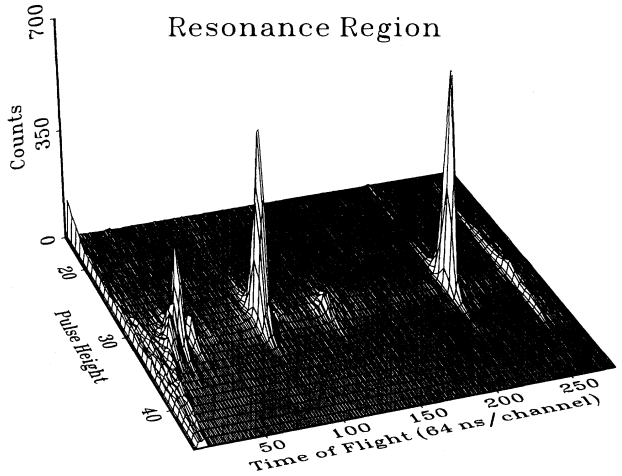

FIG. 2. Pulse-height vs time-of-flight spectra for neutron energies between about 800 eV and roughly 2 MeV. The data have been compressed by a factor of 4 along the time-of-flight axis compared to the raw data for greater clarity.

from reactions on ^{10}B is usually negligible. The only significant background is for energies above about 200 keV. The measurements made with the blank aluminum target backing were used to subtract this background from the data. The maximum correction was about 25% at the highest energy and quickly fell to less than about 2% by 400 keV. Also, from Fig. 2 it can be seen that only the lowest-energy resonance (E_n=902.6 eV) has a significant contribution from the ^{36}Cl(n,α)^{33}P reaction. Because the (n,p) and (n,α) peaks were not completely resolved from one another in this single-detector experiment it was difficult to estimate the relative sizes of the cross sections for this resonance. However, the (n,p) and (n,α) contributions were well separated in the measurements with the dual-gridded ionization chamber from which it was found that $(n,\alpha)/(n,p)=3.0$ for the E_n=902.6 eV resonance. Also, above a few hundred keV our resolution was not good enough to even partially resolve the peaks from the (n,p) and (n,α) reactions. For these reasons the cross sections we report here are actually for the sum of the (n,p) and (n,α) groups, although the (n,α) contribution appears to be very small at most energies.

III. RESULTS AND COMPARISON WITH OTHER MEASUREMENTS

The ^{36}Cl(n,p)^{36}S cross sections resulting from our measurements are shown in Figs. 3 and 4. The representative error bars shown on our data depict the one-standard-deviation relative errors only. We estimate a normalization uncertainty of about 9.5% resulting from the combined uncertainties in the ^{6}Li thermal cross section [14], the measurements of the ^{6}Li and ^{36}Cl sample sizes, and the various corrections to the data discussed above.

Our best measure of the thermal cross section comes from using our data below 10 eV where the shape of the cross section is indistinguishable from $1/v$. The weighted

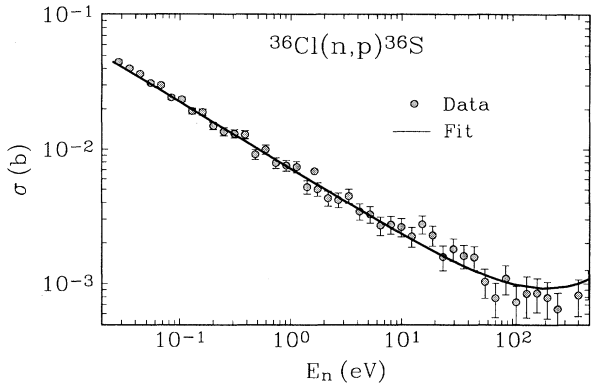

FIG. 3. The ^{36}Cl(n,p)^{36}S cross section between thermal energy and 500 eV. The circles with error bars are the data with their one-standard-deviation statistical errors. The curve is from a multilevel fit to the data as described in the text.

mean of the reduced cross sections for these energies is $\sigma\sqrt{E}=7.35\pm0.07$ mb eV$^{1/2}$, or the equivalent thermal cross section is 46.2±0.4 mb. The uncertainties given represent the statistical accuracies only. Our value for the thermal cross section is in good agreement with the value of 46±2 mb reported in Ref. [5], but disagrees with the value reported in Ref. [6] of 0.4±0.1 b.

The only other ^{36}Cl(n,p)^{36}S measurements are the resonance strengths reported in Ref. [7] which we compare to our resonance parameters in the next section. Finally, there have been no reported ^{36}S(p,n)^{36}Cl measurements to which we could compare our data.

IV. MULTILEVEL RESONANCE ANALYSIS

For s-wave neutrons incident on the $I^{\pi}=2^{+}$ target of ^{36}Cl, $J^{\pi}=\frac{3}{2}^{+}$ and $\frac{5}{2}^{+}$ levels can be excited in the ^{37}Cl compound nucleus. These levels can decay by emitting d-wave protons to the 0^{+} ground state of ^{36}S, or by emitting d-wave α particles to the $\frac{1}{2}^{+}$ ground state of ^{33}P. Decays to excited states of ^{36}S are energetically forbidden for the range of incident neutron energies we measured.

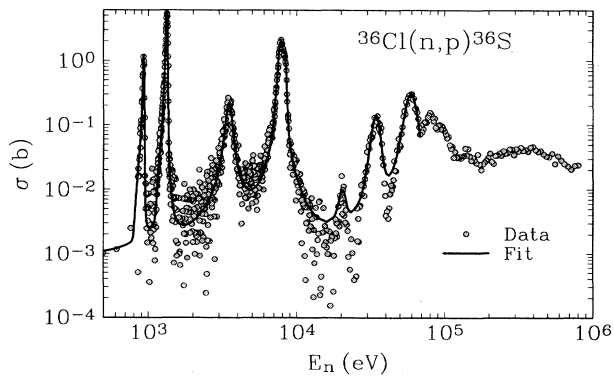

FIG. 4. The ^{36}Cl(n,p)^{36}S cross section for energies between 500 eV and 800 keV. For clarity the error bars are not shown but can be surmised from the scatter in the data. The curve is from a multilevel fit to the data as described in the text.

Alpha emission to the first two excited states of ^{33}P are allowed but are less favored because of the much smaller penetrability for the lower-energy α particles. For p-wave neutrons, levels in ^{37}Cl can be formed with $J^\pi=\frac{1}{2}^-$ through $\frac{7}{2}^-$. The $\frac{1}{2}^-$ and $\frac{3}{2}^-$ levels can decay by emitting p-wave protons or α particles whereas $\frac{5}{2}^-$ and $\frac{7}{2}^-$ levels require f waves.

In an attempt to obtain information about the resonance parameters, our data were fitted by a sum of noninterfering Breit-Wigner shapes. The fit was done between thermal energy and approximately 70 keV where the resonances appear to be reasonably well resolved. Because our resolution was broader than the widths of most of the resonances, the fit was smeared over our resolution using a skewed Gaussian function. The skew was used to account for the relatively long low-energy tail arising from the moderator and is most visible on the resonances in the keV energy region. The width of the Gaussian was calculated by adding in quadrature the energy spreads due to the pulse width of the proton storage ring (PSR) at LANSCE, $\Delta t_{\rm PSR}=0.125$ μs, the moderation time, $\Delta t_m=1.5/E^{1/2}$ μs (where E is the incident neutron energy in eV), and the channel width, $\Delta t_{\rm ch}=0.016$ μs. The skew parameters were determined in the preliminary fits to the data, and were held fixed for the remainder of the fitting. Hence, the smearing function did not add any new parameters to the fitting procedure.

There is a very limited amount of information available about the states in ^{37}Cl near the neutron threshold which can be combined with our data to better understand the structure of ^{37}Cl at these energies. It appears that the best information comes from ^{36}S$(p,\gamma)^{37}$Cl measurements [9] in which some of the same states in ^{37}Cl seen in our measurements were observed. In principal the ^{36}S$(p,\gamma)^{37}$Cl data could be combined with our ^{36}Cl$(n,p)^{36}$S data to determine the partial widths, Γ_n, Γ_p, and Γ_γ as well as E_0, Γ, and J^π. In practice, only limited information was obtainable by this method because (1) there have been no total cross-section measurements on ^{36}Cl so the neutron widths are unknown, (2) the ^{36}S$(p,\gamma)^{37}$Cl data do not extend to sufficiently high energies, (3) not all of the resonances seen in our data were resolved from each other in the ^{36}S$(p,\gamma)^{37}$Cl experiment, and (4) our resolution was usually broader than the resonance width.

Our data were fitted using the resonance energy E_0, the total width Γ, and the resonance strength $\omega\gamma=g_J\Gamma_n\Gamma_p/\Gamma$, as the three fit parameters for each resonance. The partial width in the Breit-Wigner formula were calculated from Γ, $\omega\gamma$, and $A_\gamma=(2J+1)\Gamma_\gamma\Gamma_p/\Gamma$ [from the ^{36}S$(p,\gamma)^{37}$Cl experiment [9]) in the following manner. Using $\Gamma=\Gamma_n+\Gamma_\gamma+\Gamma_p$, and the equations for A_γ and $\omega\gamma$, it can be shown that

$$\Gamma_p=\frac{\Gamma\pm[\Gamma^2-4\Gamma(10\omega\gamma+A_\gamma)/(2J+1)]^{1/2}}{2} \quad (1)$$

as well as

$$\Gamma_n=10\omega\gamma\Gamma/(2J+1)\Gamma_p \quad (2)$$

and

$$\Gamma_\gamma=A_\gamma\Gamma/(2J+1)\Gamma_p\ . \quad (3)$$

Hence, two sets of the partial widths are obtained for each J value. Sometimes one of the solutions can be eliminated by using other information. For example, the "small Γ_p" solutions are ruled out for the $E_0=3415$, 7613, and 8076 eV resonances by the fact that the resulting values of Γ_γ are much larger than expected from the systematics in this region. Also, in principle, the requirement that the quantity in the square root in Eq. (1) be greater than zero can be used to set a lower limit on the J value of the resonance if the resonance is resolved, although in practice this was not found to be very useful. Alternatively, this same condition can be used to obtain a lower limit on the total width for a given J.

For the resonances at $E_0=19\,940$, 33 740, and 58 310 eV, A_γ was not known, so we assumed $\Gamma_\gamma=1$ eV. Using this assumption results in equations for Γ_p and Γ_n similar to those given above.

Our data indicate that the $E_0=902.6$ and 1297.3 eV resonance were probably not resolved from one another in the ^{36}S$(p,\gamma)^{37}$Cl measurement [9]. Hence, we divided the reported A_γ value equally between these two resonances. Also, the resonance near $E_0=8000$ eV was reported as a doublet in the ^{36}S$(p,\gamma)^{37}$Cl measurements although only a single A_γ value was given. Our data show that there are indeed at least two resonances near this energy. Once again we split the reported A_γ value equally between the two resonances we observed at $E_0=7613$ and 8076 eV.

An estimate of the uncertainty in the parameters was obtained by holding 2 of the 3 parameters fixed at their "best fit" values while varying the other parameter until the reduced χ^2 increased by 1. These estimated uncertainties do not include any contribution from the reported uncertainties in the A_γ values. The resulting fit parameters and their estimated uncertainties are compared to previous results [5,7] in Table I. The partial widths are not given because they depend on J and can be readily calculated using Eqs. (1)–(3). With two exceptions the results from the different experiments agree to within the experimental errors. Firstly, the resonance energy for the doublet near $E_0=8000$ eV from the ^{36}S$(p,\gamma)^{37}$Cl experiment [9] is in better agreement with the energy we determined for the lower resonance of the doublet than it is with the center of the doublet. Secondly, the resonance strength of the doublet given by Gledenov *et al.* [7] is about a factor of 2 lower than our value.

Although it was not possible to determine the J^π values of the resonances, the strongest resonances are probably p wave. If these resonances are chosen to be s wave then the calculated thermal cross section is much larger than measured. However, the possibility that these resonances are s wave is not entirely ruled out because interference effects could reduce their contribution to the thermal cross section, as has been proposed for (n,α) reactions for other nuclei [17,18]. However, due to a lack of information regarding the parameters of these resonances and of the s-wave states below the neutron separation energy, it was not possible to investigate this possibility further in the present case.

TABLE I. Resonance parameters.

l	E_0 This work	E_0 Ref. [7]	E_0 Ref. [8]	Γ (eV)	$\omega\gamma$ (eV) This work	$\omega\gamma$ (eV) Ref. [7]	A_γ (eV)
0	902.6±1.3[a]			$0.84^{+2.4}_{-0.51}$[b]	(6.30±0.82)×10^{-3}		0.505[c,d]
0	$1\,297.3^{+1.1}_{-0.9}$	1.3±0.1	1.3±0.3	$3.1^{+1.8}_{-1.4}$	(7.20±0.46)×10^{-2}	(7±1)×10^{-2}	0.505[c,d]
1	3415±40	3.5±0.3	3.6±0.3	280^{+140}_{-80}	$(9.6^{+1.9}_{-1.8})\times10^{-2}$	(8±3)×10^{-2}	5.9[c]
1	$7\,613^{+35}_{-25}$	8.2±0.9	7.5±0.3	274^{+66}_{-50}	2.54±0.24	1.7±0.3	1.85[c,d]
0	$8\,076^{+41}_{-45}$			40^{+80}_{-31}[b]	0.95±0.19		1.85[c,d]
0	19 940±500			1140^{+2660}_{-1040}	0.110±0.053		4.0[e]
1	$33\,740^{+500}_{-540}$			2090^{+1160}_{-790}	$6.4^{+1.5}_{-1.1}$		4.0[e]
1	$58\,310^{+700}_{-610}$			5213^{+1600}_{-1400}	61.6±6.69		4.0[e]

[a]The width and strength given for this resonance are the sums in the (n,p) and (n,α) channels.
[b]Lower limit on Γ from the condition that the quantity in the square root in Eq. (1) be positive. Calculated with $J=\frac{5}{2}$.
[c]A_γ from Ref. [8].
[d]A_γ from Ref. [8] divided equally between two resonances observed in the present work.
[e]A_γ from our fit assuming $\Gamma_\gamma=1.0$ eV and $J=\frac{3}{2}$, and taking the "+" sign in Eq. (1).

The fit to the data is shown as the solid curve in Figs. 3 and 4. The data from thermal energy to about 70 keV are well fitted by the parameters given in Table I with the exception that the fit between the higher-energy resonances is higher than the data. This may be due to interference effects, or perhaps it indicates that these higher-energy peaks are due to more than one resonance. This latter possibility is strengthened by the fact that we observed five resonances in the first 10 keV above threshold and only three in the next 60 keV.

V. NUCLEOSYNTHESIS OF ^{36}S

The astrophysical reaction rate, $N_A\langle\sigma v\rangle$, calculated by numerical integration over our data is shown in Fig. 5. Also shown are the rates for the ^{36}Cl(n,p), (n,α), and (n,γ) reactions from a statistical model calculation [19],

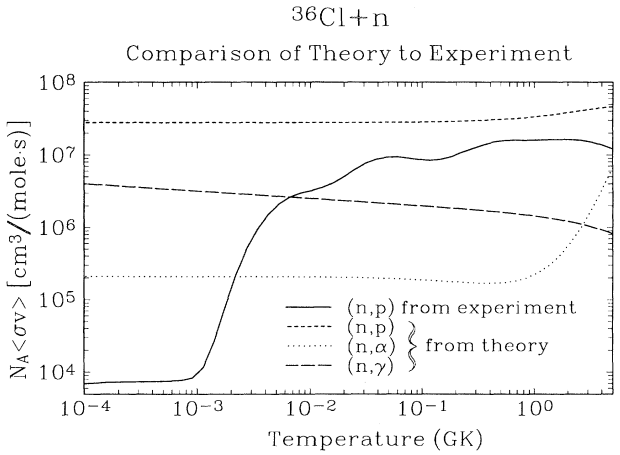

FIG. 5. Astrophysical reaction rates, $N_A\langle\sigma v\rangle$, for ^{36}Cl$+n$ reactions. The solid curve was calculated by numerical integration over our cross sections shown in Figs. 3 and 4. The short-dashed, dotted, and long-dashed curves are the rates for the ^{36}Cl(n,p), (n,α), and (n,γ) reactions, respectively, from the statistical model calculations of Ref. [19].

which have been used in most nucleosynthesis calculations. At the temperature of the s process ($T\approx0.35$ GK), the theoretical rate for the (n,p) reaction is a factor of 2.2 larger than our measurement.

The reduction in the ^{36}Cl$(n,p)^{36}$S reaction rate indicated by our measurements should help to reduce the overproduction of ^{36}S seen in explosive nucleosynthesis calculations, and may significantly reduce the amount of ^{36}S calculated to be synthesized by the s process. The mass flow in the region affecting the abundance of ^{36}S is complicated by several branchings, so new nucleosynthesis calculations are needed to fully assess the impact of our new rate. For example, in the s process once the flow has gone past ^{36}Cl it can cycle back to ^{36}S directly via ^{39}Ar$(n,\alpha)^{36}$S, or indirectly via ^{41}Ca$(n,\alpha)^{38}$Ar, or even possibly ^{37}Ar$(n,\alpha)^{34}$S.

Also, since the time of the last published calculations several new measurements have been made, on ^{33}S$(n,\alpha)^{30}$Si [20], ^{35}Cl$(n,p)^{35}$S [21,22], and ^{41}Ca$(n,\alpha)^{38}$Ar [22]. Furthermore, the s-process calculations of Ref. [4] were made with an exponential distribution of exposures whereas it is now thought that the weak component of the s-process results in a single exposure [23]. Of the remaining unmeasured cross sections of importance to the s process several appear to be amenable to direct measurements. These include the ^{39}Ar$(n,\alpha)^{36}$S, ^{37}Ar$(n,\alpha)^{34}$S, and ^{36}S$(n,\gamma)^{37}$S reactions. The unmeasured ^{36}Cl$(n,\gamma)^{37}$Cl reaction is also very important because it competes directly with the ^{36}Cl$(n,p)^{36}$S reaction. Statistical model calculations [19] of the ratio of cross sections for ^{36}Cl at 30 keV yielded $(n,p)/(n,\gamma)\approx20$. At thermal energy,the results of the present work together with the ^{36}Cl$(n,\gamma)^{37}$Cl measurements of Ref. [24] yield a ratio of $(n,p)/(n,\gamma)\approx5\times10^{-4}$, or about 40 000 times smaller than the theoretical rate at 30 keV. However, there appears to be some disagreement about the value of the thermal ^{36}Cl$(n,\gamma)^{37}$Cl cross section. In the measurements of Ref. [24] this cross section was found to be $\sigma_{\rm th}=90\pm25$ b. On the other hand, the cross section was measured to be $\sigma_{\rm th}<10$ b in Ref. [25]. It is this latter value that is quoted in compilations [26,27] although

there does not seem to be any reason to prefer it over Ref. [24]. The resonance parameters we determined in Sec. IV could in principal be used to estimate the ^{36}Cl$(n,\gamma)^{37}$Cl cross section. In practice, the parameters are too uncertain to allow a useful estimate to be made. However, some general conclusions can be drawn. Firstly, even if the most optimistic set of parameters is chosen (i.e., all resonances are s wave, and the "small Γ_p" solution is chosen except for those cases where this would lead to $\Gamma_\gamma \geq 2$ eV) the calculated ^{36}Cl$(n,\gamma)^{37}$Cl cross section (neglecting interference effects) is less than 0.5 b—much less than the measured value of 90±25 b [24]. Perhaps a subthreshold resonance could account for the large thermal ^{36}Cl$(n,\gamma)^{37}$Cl cross section while at the same time suppressing the thermal ^{36}Cl$(n,p)^{36}$S cross section. Secondly, for the 902.6 1297.3, and 19940 eV resonances it is possible to have $\Gamma_\gamma/\Gamma_p \approx 3-6$. For the broader resonances this ratio is smaller that about 10^{-2}. However, the higher-energy peaks in our data are very probably due to more than one resonance, so the ratio we obtained is very uncertain and is most likely an underestimate. A direct measurement of the ^{36}Cl$(n,\gamma)^{37}$Cl cross section at thermal energy seems feasible with current techniques and is highly desirable in light of the present large uncertainty. A direct measurement of the ^{36}Cl$(n,\gamma)^{37}$Cl cross section at astrophysically interesting temperatures appears very difficult if it is as small as the statistical model calculation indicates. Finally, these same cross sections are needed for explosive nucleosynthesis calculations, although the reaction network is more complicated and charged-particle reactions also play a role and may dominate in some scenarios.

VI. CONCLUSIONS

We have measured the ^{36}Cl$(n,p)^{36}$S cross section from thermal energy to approximately 800 keV. In a multilevel analysis of our data as well as information from ^{36}S$(p,\gamma)^{37}$Cl measurements [9], we determined parameters for eight resonances in the energy range from 900 eV to 70 keV. At astrophysically relevant temperatures ($T \approx 0.1-1.0$ GK), the reaction rate, $N_A\langle\sigma v\rangle$, calculated from our data is roughly a factor of 2 times smaller than the theoretical rate [19] used in previous nucleosynthesis calculations. The new, lower rate should help to reduce the overproduction of ^{36}S from explosive nucleosynthesis calculations and may significantly reduce the amount of ^{36}S calculated to be synthesized in the s process.

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