INVESTIGATION OF THE ASTROPHYSICAL ^{36}S(p,γ)^{37}Cl REACTION AT $E_{\rm p}$=1975...2190 keV

A.N. Vodin[1*]***, I.V. Ushakov***[1]***, G.K. Khomyakov***[1]***, G.E. Tuller***[1]***, L.P. Korda***[1]***, I.A. Shapoval***[1,2]***, A.V. Tertichnyi***[1,2]

[1]*National Science Center "Kharkov Institute of Physics and Technology", 61108, Kharkov, Ukraine*

[2]*V.N. Karazin Kharkov National University, Kharkov, Ukraine*

(Received July 15, 2009)

The ^{36}S(p,γ)^{37}Cl reaction was investigated in the proton energy range $E_{\rm p}$=1975-2190 keV. The observed resonance strengths were evaluated. The γ-decay schemes of the resonances at $E_{\rm p}$=2037, 2058, 2069, 2080, 2122 and 2165 keV were constructed and the total γ-widths were determined. The astrophysical ^{36}S(p,γ)^{37}Cl reaction rate was estimated.

PACS: 24.30.-v, 25.40.Lw, 25.70.Ef, 25.70.Gh

1. INTRODUCTION

The experimental determination of nuclear reaction effective cross-sections, which are necessary for the creation of model representations of nucleosynthesis in the process of stellar evolution, is one of the main problems of astrophysics.

Special attention has been recently paid to the problem of the rare isotope ^{36}S (0.017%) generation [1]. It is known [2],[3], that one of the sources is the ^{36}Cl(n,p)^{36}S reaction, which goes through the compound ^{37}Cl nucleus. However, the data on spins J and total radiation widths Γ_γ are missing for most of the neutron resonances, which makes it impossible to carry out a qualitative analysis of the resonance curve shape observed in the ^{36}Cl(n,p)^{36}S reaction. Meanwhile, the missing information on neutron resonances can be obtained with the help of additional measurements that lead to the same compound ^{37}Cl nucleus (see Fig.1).

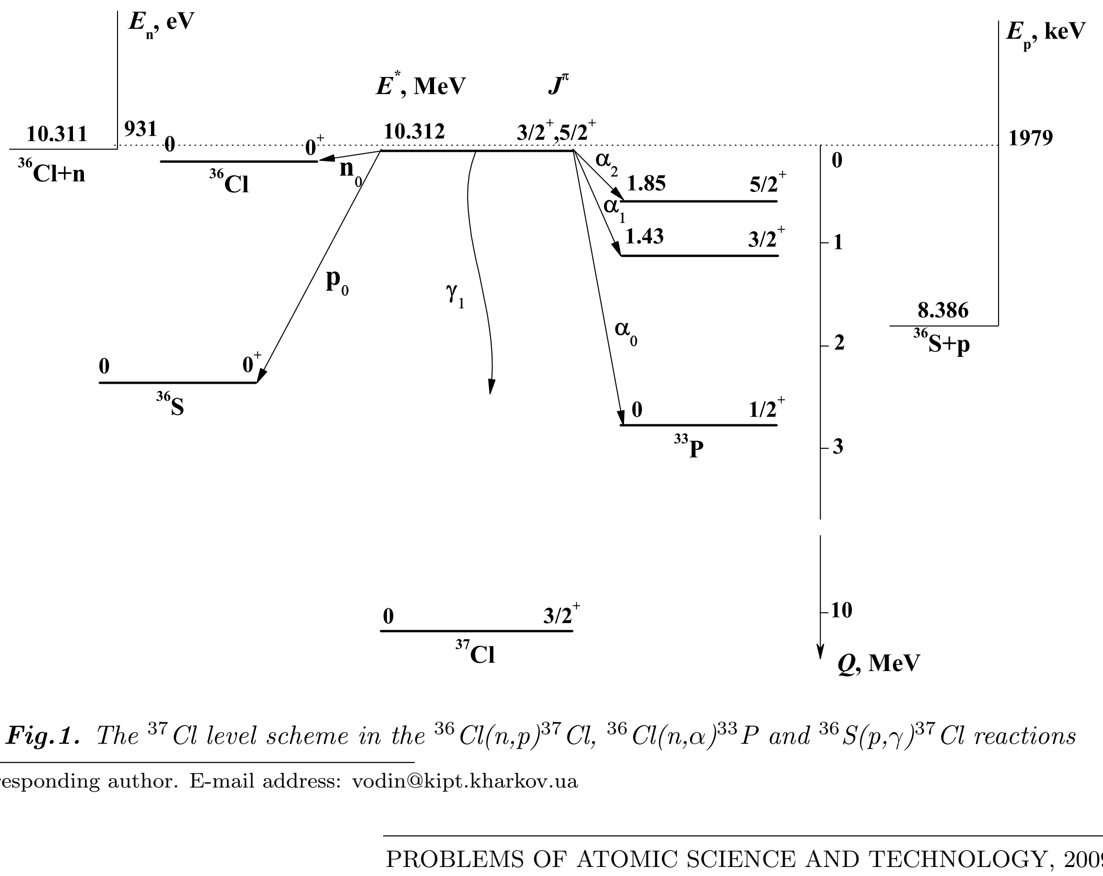

Fig.1. *The ^{37}Cl level scheme in the ^{36}Cl(n,p)^{37}Cl, ^{36}Cl(n,α)^{33}P and ^{36}S(p,γ)^{37}Cl reactions*

*Corresponding author. E-mail address: vodin@kipt.kharkov.ua

It appears from the experimental data [4], that ^{37}Cl excited levels can be observed both in the ^{36}Cl(n,p)^{36}S reaction and in the ^{36}S(p,γ)^{37}Cl reaction. In this context a series of researches was carried out. The excitation function of the ^{36}S(p,γ)^{37}Cl reaction was studied in the proton energy range E_p =1975...2190 keV, which corresponds to excitation of neutron resonances in the ^{36}Cl(n,p)^{36}S reaction in E_n =0.5...250 keV (see Table 1). As a result, we determined the energy positions and strengths S of resonances observed in the specified range of proton energies. The γ-decay schemes of the most intensive resonances at E_p=2037, 2058, 2069, 2080, 2122 and 2165 keV were constructed and the total γ-widths were determined. Taking into account the obtained data on the strengths, the astrophysical ^{36}Cl(n,p)^{36}S reaction rate was estimated.

Table 1. *Resonances in the ^{36}Cl(n,p)^{36}S and ^{36}S(p,γ)^{37}Cl reactions*

No.	^{36}Cl(n,p)^{36}S		^{36}S(p,γ)^{37}Cl				
	E_n, eV	E^*, keV	E_p, keV	E^*, keV	$2J^\pi$	S, eV	Γ_γ, eV
1	931(1)	10311.9	-	-	1^+		
2	1341(2)	10312.3	1979.5	10312.3	$(3,5)^-$	1.0	(0.3,0.2)
3	3570(50)	10314.4	1982.1	10314.9	$(3,5)^+$	5.0	(1.3,0.8)
4	7937(15)	10318.7	1986.2	10318.9	3^+	4.0	1.0
5	8400(20)	10319.1	-	-	$(3,5)^-$		
6	-	-	1994.5	10326.9		0.69	
7	21100(300)	10331.5	1997.6	10330.0	1^+	0.18	0.09
8	-	-	2002.8	10335.0		0.09	
9	34400(200)	10344.4	2012.1	10344.1	$(3,5)^-$	3.3	(0.8,0.6)
10	37200(100)	10347.2	2014.2	10346.1		8.6	
11	-	-	2022.5	10354.2		1.4	
12	50750(200)	10360.3	2028.8	10360.3		2.7	
13	61700(200)	10371.0	2037.1	10368.4	3^+	40.3	10.0
14	-	-	2041.8	10373.0		3.2	
15	-	-	2046.5	10377.5		0.08	
16	-	-	2050.7	10381.6		1.2	
17	82700(800)	10391.4	2058.1	10388.8	$(3,5)^+$	16.9	(4.2,2.8)
18	-	-	2065.4	10395.9		1.0	
19	94400(800)	10402.8	2068.6	10399.0	$(3,5)^+$	11.6	(2.9,1.9)
20	-	-	2073.9	10404.2		0.91	
21	106500(500)	10414.6	2080.2	10414.6	3^+	19.9	5.0
22	112700(1000)	10420.6	2086.5	10416.4		2.1	
23	-	-	2092.9	10422.7		0.32	
24	-	-	2099.3	10428.9		0.21	
25	-	-	2101.4	10430.9		0.43	
26	-	-	2106.6	10436.0		1.9	
27	-	-	2112.0	10441.3		0.19	
28	-	-	2115.2	10444.4		0.15	
29	151000(1500)	10457.9	2121.6	10450.6	3^+	22.9	5.7
30	-	-	2125.5	10454.4		1.0	
31	-	-	2134.4	10463.1		0.91	
32	-	-	2137.3	10465.9		0.92	
33	-	-	2143.0	10471.4		2.4	
34	-	-	2149.4	10477.6		0.55	
35	-	-	2153.4	10481.5		0.09	
36	-	-	2156.6	10484.7		0.12	
37	-	-	2160.4	10488.4		1.2	
38	196000(1500)	10501.7	2165.2	10493.0	3^+	23.2	5.8
39	-	-	2171.0	10498.7		1.0	
40	208500(3000)	10513.8	2176.0	10503.5		7.4	
41	-	-	2182.5	10509.9		0.06	
42	-	-	2184.6	10511.9		0.03	

2. EXPERIMENTAL TECHNIQUE

The investigations were carried out using the proton beam of the ESA-5 electrostatic accelerator at the Nuclear Spectroscopy Laboratory (NSC KIPT). The proton current on the target was up to 10 μA. The bombarding energy was calibrated with wellknown resonances of the $^{27}Al(p,\gamma)^{28}Si$ reaction (E_R=992 and 1317 keV). The energy spread was 0.4 keV. A target of approximately 4 keV thickness at E_p=2 MeV consisting of Ag_2S (81.1% ^{36}S) was used.

The spectra of γ-rays, arising from the decay of resonance states in ^{37}Cl, were measured with the 70 cm^3 Ge(Li)-detector. The energy resolution was about 3.0 keV for ^{60}Co γ-lines. The efficiency was determined with calibrated standard sources and using relative γ-ray intensities in the $^{27}Al(p,\gamma)^{28}Si$ reaction. To reduce the low-energy γ-background, we used a combined lead-copper protection of the Ge(Li)-detector.

To obtain a yield curve of the $^{36}S(p,\gamma)^{37}Cl$ reaction as a function of proton energy a spectrometer based on a 150×100 mm NaI(Tl) crystal were used. The experiments were performed on the spectrometric equipment designed in the CAMAC standard and operating on-line with a personal computer.

3. RESULTS

The excitation function of the $^{36}S(p,\gamma)^{37}Cl$ reaction was measured in the proton energy range E_p=1965...2190 keV. We established the positions of 40 resonances, identified as the excited states of ^{37}Cl (see Table 1). In this case, Q of the reaction was taken to be 8386.34(23) keV, according to [5]. The results obtained are in good agreement with [6].

The γ-decay spectra were measured for the resonances at E_p=2037, 2058, 2069, 2080, 2122 and 2165 keV. The decay schemes of the resonances were constructed on the basis of the balance of energies and intensities for the observed transitions, taking into account all the known data on the levels of ^{37}Cl [5]. The branching ratios b_γ for all six resonances are listed in Table 2.

4. DATA ANALYSIS

4.1. Resonance strengths and γ-widths

The radiative width Γ_γ of a resonant level was calculated on the basis of the data on the strength S and the proton decay width Γ_p of the resonance. The value of S was determined from the expression[7]:

$$S = (2J+1)\frac{\Gamma_p\Gamma_\gamma}{\Gamma} = (2I+1)\frac{1}{(\pi\lambda)^2}\frac{M}{m_p+M}\frac{\varepsilon N_\gamma}{b\cdot f\cdot E\cdot W(\theta)}\frac{e}{Q}, \quad (1)$$

where J is the spin of the resonant state; Γ_p and Γ_γ are, respectively, the proton and radiative resonance widths; Γ is the total resonance width; I is the target nucleus spin; λ is the incident proton wavelength; M is the mass number of a target nucleus; m_p is the proton mass; ε is the bremsstrahlung loss in the target ($eV\cdot cm^2\cdot atom^{-1}$); N_γ is the γ-yield; b_γ is the branching ratio; f is the number of target nuclei per atom; E is the absolute detector efficiency; $W(\theta)$ is the angular distribution of γ-photons (see below); e is the elementary charge; and Q is the integrator charge. To avoid the errors related to the anisotropy of the angular distribution of γ-photons, the γ-decay spectra of resonances were measured at the angle θ_{lab}=55°, at which $W(\theta)\approx 1$.

Table 2. *γ-Decay schemes of high excited states in ^{37}Cl*

E_f^*, MeV	$2J_f^\pi$	E_p(keV), E_i^*(MeV), $2J_i^\pi$					
		2037 10.368 3^+	2058 10.389 $(3,5)^+$	2069 10.399 $(3,5)^+$	2080 10.410 3^+	2122 10451 3^+	2165 10.493 3^+
0	3^+	25	26	11	98	55	37
1.727	1^+	66	27			22	35
3.086	5^+		18		1	4	
3.104	7^-			11			
3.708	$3^{(+)}$					6	10
4.016	3^+					4	
4.177	3^-					2	10
4.273	7^-			19			
4.396	5					2	
4.801	5^+			2	1		
4.854	3					2	
4.961	3		20				
5.059	$(3^-$-$7^+)$						6
5.373	(1-5)	10	9				
5.406	(1,3)					1	
5.617	(1-5)					2	
5.944				29			
6.488				18			
6.669	$(3,5)^+$			9			3

The strength of the resonance under study, S_i, is determined through the calibration resonance strength S_k at E_p=1887 keV, which is equal to 31.0(3) eV [8]. For the case $Q_k = Q_i$, the quantities S_i and S_k are related by a relatively simple expression:

$$S_i = S_k \frac{\lambda_k^2}{\lambda_i^2} \frac{\varepsilon_i N_\gamma^i b_k E_k}{\varepsilon_k N_\gamma^k b_i E_i}\,, \tag{2}$$

where the indices "k" and "i" correspond to the calibration and investigated resonances, respectively. The thus obtained values of S for the resonances under study are listed in Table 1.

The radiation widths Γ_γ were definitely obtained only for the resonances at E_p=2037, 2058, 2069, 2080, 2122 and 2165 keV, for which spin values were established in [9]. The Γ_γ value was calculated with the data on resonance strengths S, under the assumption that $\Gamma_p >> \Gamma_\gamma$. In this case

$$S \approx (2J+1)\Gamma_\gamma, \tag{3}$$

and the resonance strength is completely defined by Γ_γ. The obtained results are listed in Table 1.

4.2. Reaction rate

One of the main characteristics of the astrophysical (p,n) or (p,γ)-reactions is the total rate, that can be expressed via the temperature as following (in units of cm^3·s^{-1}·mole^{-1}) [10]:

$$N_A\langle\sigma\nu\rangle = 3.731\cdot 10^{10}\mu^{-\frac{1}{2}}T_9^{-\frac{3}{2}}\int_0^\infty \sigma(E)Ee^{-11.605\frac{E}{T_9}}dE, \tag{4}$$

where E is the incident particle energy in the center-of-mass system in MeV, T_9 is the temperature in GK, μ is the reduced mass in a.m.u. The total reaction cross-section σ(in barn) is determined by the sum of resonance and non-resonance contributions to a mechanism of the nuclear reaction. Meanwhile the contribution of isolated and narrow resonances into the total astrophysical reaction rate can be calculated by [10]:

$$N_A\langle\sigma\nu\rangle_r = 1.540\cdot 10^{11}(\mu T_9)^{-\frac{3}{2}}\sum_i \omega\gamma_i e^{-11.605\frac{E_{Ri}}{T_9}}, \tag{5}$$

where E_{Ri} are the resonance energies and $\omega\gamma_i$ is the resonance strengths in MeV. The ^{36}S(p,γ)^{37}Cl, ^{36}S(p,n)^{36}Cl and ^{36}S(p,α)^{33}P reaction rate curves, calculated according to [11] and the ^{36}S(p,γ)^{37}Cl reaction rate with taking into account the obtained experimental data on the strengths are shown in Fig.2. It can be seen that contribution of the studied resonances to the total astrophysical ^{36}S(p,γ)^{37}Cl reaction rate in the stellar temperature range of (0.01-1)T_9 is insignificant. However at temperatures higher than 1T_9 it becomes comparable with the ^{36}S(p,α)^{33}P reaction contribution to the total proton reaction rate on the ^{36}S nuclei.

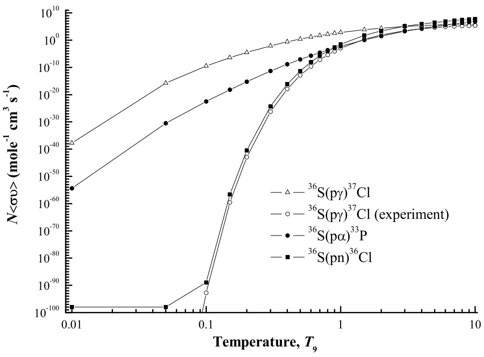

Fig.2. *The ^{36}S(p,γ)^{37}Cl, ^{36}S(p,n)^{36}Cl and ^{36}S(p,α)^{33}P reaction rates*

5. CONCLUSIONS

In this paper we obtained the radiation decay widths for the neutron resonances observed in the ^{36}Cl(n,p)^{36}S reaction by using the ^{36}S(p,γ)^{37}Cl reaction. In this context, the ^{36}S(p,γ)^{37}Cl reaction yield was measured in the accelerated proton energy range E_p=1975...2190 keV, where we established the positions of 40 resonances and determined their strengths. This allowed to evaluate the contribution of the resonances in the total rate of the astrophysical ^{36}S(p,γ)^{37}Cl reaction.

The obtained radiation widths for the resonances at E_p=2037, 2058, 2069, 2080, 2122 and 2165 keV can be used as input parameters while analyzing a resonance curve shape of the ^{36}Cl(n,p)^{36}S reaction, which is of interest to astrophysics in solving the problem of ^{36}S isotope generation.

References

1. P. Shalanski et al. *About Possibilities of Nucleosynthesis Modeling Using Computer Systems. Elements Production in the S-Cl Region During Helium Burning in 25$M_\odot$ Stars*: Preprint JINR, P10-2001-161. Dubna, 2001(in Russian).

2. Y.M. Gledenov, Y.P. Popov and V.I. Salatsky Study of the ^{36}Cl(n,p)^{36}S reaction in the neutron energy range up to 10 keV//*Z. Phys.* A. 1985, v.322, p.685.

3. P.E. Koehleret et al. ^{36}Cl(n,p)^{36}S cross section from 25 meV to 800 keV and the nucleosynthesis of the rare isotope ^{36}S//*Phys. Rev.* C. 1993, v.47, p.2107.

4. L. De Smetet et al. Experimental determination of the ^{36}Cl(n,p)^{36}S and ^{36}Cl(n,α)^{33}P reaction cross sections and the consequences on the origin of ^{36}S//*Phys. Rev.* C. 2007, v.75, p.034617.

5. P.M. Endt. Energy levels of A=21-44 nuclei (VII)//*Nucl. Phys.* A. 1990, v.521, p.1.

6. G.J.L. Nooren and C. Van der Leun The reaction ^{36}S(p,γ)^{37}Cl (I)//*Nucl. Phys.* A. 1984, v.423, p.197.

7. A. Anttila, J. Keinonen, M. Hauntala and I. Forsblom. Use of the ^{27}Al(p,γ)^{28}Si, E_p=992 keV resonance as a gamma-ray intensity standard//*Nucl. Instrum. Methods.* 1977, v.147, p.501.

8. A.N. Vodin, A.S. Kachan and V.M. Mischenko. The $f_{7/2}$ analog resonances in odd nuclei of the 1d2s-shell//*Izv. RAN. Ser. Phys.* 2002, v.66(1), p.40.

9. A.S. Kachan et al. Resonance-like structure in the ^{36}S(p,γ)^{37}Cl reaction//*Probl. At. Sc. and Techn. Ser. Nucl. Phys. Invest.* 2004, v.5(44), p.39.

10. C. Iliadis et al. Proton-induced thermonuclear reaction rates for A=20-40 nuclei//*The Astrophys. J. Sup. Series.* 2001, v.134, p.151.

11. http://nucastro.org/reaclib.html

ИССЛЕДОВАНИЕ АСТРОФИЗИЧЕСКОЙ РЕАКЦИИ ^{36}S(p,γ)^{37}Cl ПРИ E_p=1975...2190 кэВ

А.Н. Водин, И.В. Ушаков, Г.К. Хомяков, Г.Э. Туллер, Л.П. Корда, И.А. Шаповал, А.В. Тертичный

Представлены результаты исследований реакции ^{36}S(p,γ)^{37}Cl в области энергий протонов E_p=1975...2190 кэВ. Оценены силы наблюдаемых резонансов. Построены схемы распада резонансов при E_p=2037, 2058, 2069, 2080, 2122 и 2165 кэВ. Рассчитаны полные радиационные ширины распада резонансов. Проведена оценка скорости астрофизической реакции ^{36}S(p,γ)^{37}Cl.

ДОСЛІДЖЕННЯ АСТРОФІЗИЧНОЇ РЕАКЦІЇ ^{36}S(p,γ)^{37}Cl ПРИ E_p=1975...2190 кеВ

О.М. Водін, І.В. Ушаков, Г.К. Хомяков, Г.Е. Туллер, Л.П. Корда, І.А. Шаповал, А.В. Тертичний

Представлено результати досліджень реакції ^{36}S(p,γ)^{37}Cl в області енергій протонів E_p=1975...2190 кеВ. Оцінено сили спостережуваних резонансів. Побудовано схеми розпаду резонансів при E_p=2037, 2058, 2069, 2080, 2122 та 2165 кеВ. Розраховані повні радіаційні ширини розпаду резонансів. Проведено оцінку швидкості астрофізичної реакції ^{36}S(p,γ)^{37}Cl.