A INVESTIGATION OF CHARACTERISTICS OF THE REACTION $^{16}O(p,\gamma)^{17}F$ AT ASTROPHYSICAL ENERGIES

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Excitation functions of the capture (DC → 494 keV) reaction $^{16}O(p,\gamma)^{17}F$ have been obtained at $\theta_\gamma = 90^0$ and $E_p = 550 \div 1100$ keV with the use ZrO_2 solid targets. Detailed angular distributions were obtained at $E_p = 1100$ keV. The differential cross section of direct radiative capture (DC → g. s.) reaction $^{16}O(p,\gamma)^{17}F$ is calculated by using cluster folding potential. This potential was tested by description of elastic scattering at energy of 17 MeV. Good agreement for cross section of the $^{16}O(p,\gamma)^{17}F$ reaction with experimental values and results of the other theoretical works is achieved. Astrophysical S-factor and thermonuclear reaction rates (DC → g. s.) are obtained by using results of the calculated and new experimental data. Calculated S-factor agrees with results from other theoretical works. The calculation of thermonuclear reaction rates shows their great sensitivity to low energies range of Maxwell distribution.

Keywords: nuclear reactions cross section, astrophysical S-factor, differential cross section, direct radiative capture, cluster wave function, cluster folding potential.

Introduction

A study of protons radiative capture reactions on nuclei allows to obtain both truly nuclear information about structure of nuclei, energy spectra and a nuclear fusion, an elements occurrence and so on. Besides, the study of these reactions is necessary for a diagnostics of thermonuclear plasma and a search of new alternative kinds of fuel for controlled thermonuclear fusion.

One of the most interesting reactions is $^{16}O(p,\gamma)^{17}F$. This reaction is in the chain of the "CNO"-cycle of light elements production. The cross section of this reaction is significantly lower than that for other reaction of a proton capture by light nuclei. The main measurements of differential and total cross-sections of this reaction were carried out in the 70's already and summarised in the known work [1]. However during the extraction of astrophysical data from the reaction there are observed difficulties, which are common for all reactions of radioactive capture. In bowels of the Sun and stars this reaction takes place at comparatively low energies of interacting particles (of the order of tens keV~10^7K). In contemporary accelerators, an achievement of such energies is a complicated problem, therefore there is carried out the procedure of cross sections extrapolation (or S-factors as the more easy function of energy) into the region of lower energies.

In last years, new measurements of direct radioactive capture to the first excited level and to the ground state of the nucleus ^{17}F have carried out [2]. In our work, taking into account new measured data on differential and total cross- sections in the interval of from 0.35 to 1.0 MeV, such values as the astrophysical S-factor, a penetrability of a potential barrier and reactions rates have been calculated.

Within the framework of the method of distorted waves there were made calculations of differential cross-sections for the reaction of radiative capture by E1 and E2 transition with use of data at energies of (0.35÷1.0) MeV. To describe the input channel there was used a cluster-folding potential of an interaction of proton with the nucleus ^{16}O, obtained by using of the approach developed in the work [3]. In this approach a nucleus target was considered as the two-cluster system (α-^{12}C), thus an internal structure of clusters did not considered. Results of calculations are compared with data of other works [1, 2, 4 – 5].

Experimental procedure and result

Proton beams of 10 μA were provided by the 2 MV "RAC-2-1" accelerator at the Institute of Nuclear Physics of Almaty. As targets there were used fine films of zirconium oxide ZrO_2 (sprayed

onto copper base) with natural composition of oxygen and with thicknesses of (18, 25, 30 and 42) $\mu g/cm^2$. Details concerning arrangement and the conducting of experiment have been recently described [6].

There were measured angular distributions of differential cross sections of the reaction $^{16}O(p,\gamma)^{17}F$ at the proton energy, E_p=1100 keV, for the most important (from the astrophysical point of view) capture onto the level E = 495 keV of the nucleus ^{17}F. Experiments were carried out for angles θ_γ (0°, 45°, 90° and 135°) to the proton beam direction (**Fig.1**). For the angle 135° data were obtained for the first time. There were determined differential cross sections of the capture reaction $^{16}O(p,\gamma)^{17}F$ on to the level E = 495 keV of the nucleons ^{17}F in the proton energy interval, E_p = 550 ÷ 1100 keV, at the angle 90° (**Fig.2**.). Because the given energy interval is far from resonances of the reaction $^{16}O(p,\gamma)^{17}F$, the its dominant mechanism is the direct capture with the constant (not depending on proton energy) angular distribution of cross sections [1]. Thus, obtained differential cross section of direct radiative capture (DC → 494 keV) reaction $^{16}O(p,\gamma)^{17}F$ in all an angle range in the given interval of energy of protons. In a **Fig. 1** and **Fig. 2** obtained experimental data in comparison with data of work [1] are presented.

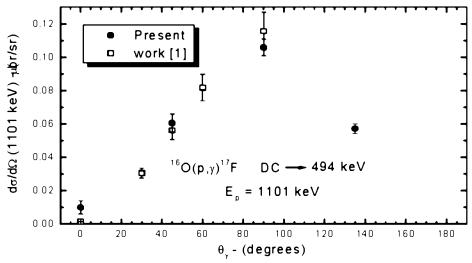


Fig. 1. Angular distributions for the DC → 494 keV γ - ray transitions as observed in the reaction $^{16}O(p,\gamma)^{17}F$ at E_p = 1101 keV.

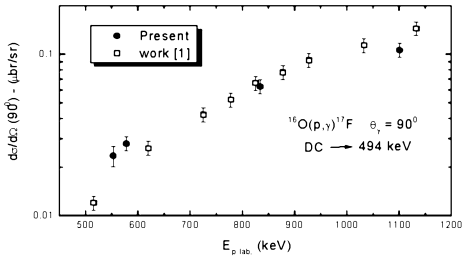


Fig. 2. Differential cross section for the DC → 494 keV γ - ray transitions as observed in the reaction $^{16}O(p,\gamma)^{17}F$ at θ_γ = 90°.

For completeness of a picture of radiative capture the theoretical calculation of cross sections, S-factor and reaction rates on the ground state was carried out.

Calculation of differential cross section for E1 transition and astrophysical S-factor.

For description of (p,γ) reaction a direct radiative capture model within the framework of two-body approach have been used. The hamiltonian operator have taken into account only E1 and E2-transition.

For description of initial and final states it is necessary to have an interaction potential, which describes bound and scattering states of (^{16}O+p) system

As a rule, for determination of an optical potential microscopically founded the folding model of a nucleon - nucleon potential on nucleon density is used [7]. The nucleon density is extracted from the data on elastic scattering of electrons or nucleones by nuclei. Depending on selection of the nucleon - nucleon potential and nucleon density the model gives a type of the potential. Then the obtained potential is updated by adjustment under experimental data on elastic scattering.

In this work, a new method of an optical potential determination - cluster folding model, where cluster - cluster potentials are folded on cluster density, is offered. The given method was offered in the work [3] on an optical interaction potential determination of the system (d-^{6}Li), where the folding procedure was performed on central interaction. In our work this approach was improved for a more general case of potentials splitted by parity [8].

The ^{16}O nucleus is considered as a ground state of two-cluster system (α-^{12}C), and the internal cluster degree of freedom are frozen. The indication onto a high probability of such structure of the ^{16}O nucleus serves the energetical fact, that bound energy in the channel (α-^{12}C), is equal to 7.16 MeV, while the threshold of the dissociation in the channel (p-^{15}N) is equal to 12.13 MeV [9]. In the ground state the wave function of relative motion of the (α-^{12}C)-system, in accordance with the Pauli's exclusion principle has two nodes and orbital moment L=0.

For obtaining the p-^{16}O folding-potential, we have folded (cluster - cluster) interaction (p-α) and (p-^{12}C) onto (α-^{12}C) density:

$$V(\vec{y}_1) = \int d\vec{x}\Psi(\vec{x}_1)\left[V_{p-^{12}C}(\vec{x}_2) + V_{p-\alpha}(\vec{x}_3)\right]\Psi(\vec{x}_1) \ . \qquad (1)$$

The wave function of relative motion of (α-^{12}C)-system, $\Psi(\vec{x}_1)$, is generated in the Wood-Saxon's form of the potential, which was offered in work [10]. Its parameters for the moment L=0, well reproduce elastic scattering phase: V_0 = - 45.55 MeV; R_n= 3.55 fm; a=0.6 fm. The potentials of (N-α)- and (N-^{12}C)-interaction in the Gaussian form are selected upon such condition, in order to well describe experimental data on elastic scattering. In our calculations we have neglected spin-orbital term of potentials. In particular we have the following potentials:

a) an interaction potential of (p-α).

The given potential was selected from the work [11]. This potential is a deep potential with forbidden states and is one of the best ones. The authors of the work [11] have selected it because it most fully reproduces low energy experimental phases of elastic scattering. This potential was successfully tested in three-cluster models of nuclei with A=6 and 9 [11, 12]. It has the form

$$V(r) = V_0 \exp(-\eta r^2)$$

with parameters for even waves: V_0=-66.580 MeV, η=0.6203 fm^{-2}; for odd waves V_0=-46.303 MeV, η=0.4302 fm^{-2}. This potential, in accordance to the Pauli's exclusion principle, has one forbidden state in a S-wave.

b) an interaction potential of the (p-^{12}C).

The given potential was selected from the work [13]. This potential is a deep potential with forbidden states. This potential reproduces low energy experimental phases of elastic scattering. This potential was tested in reaction of direct radioactive capture (^{12}C (p,γ) ^{13}N). It has the form

$$V(r) = V_0 \exp(-r^2 / a^2)$$

with parameters for even waves: V_0= -97.840 MeV, a=2.1fm; for odd waves V_0=-93.090 MeV, a=1.92fm. Also this potential, in accordance to the Pauli's exclusion principle, has one forbidden state in a S-wave.

The calculated folding-potential was obtained in numerical form, and for further convenience was parameterised in the Wood-Saxon's form

$$V(r) = \frac{V_0}{1 + \exp\left(\dfrac{r - R_0}{a}\right)} \quad , \qquad (2)$$

with parameters: V_0 = -115.0 MeV, R_0=1.714 fm, a = 0.769 fm. The potential contains only central part.

The calculated potential was tested on description of elastic scattering protons by ^{16}O-nuclei at energy of 17 MeV. For calculation within the framework of optical model the standard "ECIS94"-programme was used [14]. All other optical potential parameters were extracted from the Perry's formula [15]. The parameter V_0 varied for description of bound state. The parameters V_0 for real

part and other imaginary and spin-orbital optical parameters varied, too. Obtained potential parameters describe experimental angular distribution [16] from 30 to 120 grades.

Differential and total cross sections of direct radioactive capture are calculated for transition to a ground state of the ^{17}F nucleus with quantum numbers J^{π},T=5/2^{+},1/2 and relative orbital moment L=2. It is known, that the main contribution to transition matrix element gives E1-multipole of a partial wave of an continuum spectrum with L=1. The differential cross section depending on energy of positive protons is calculated for two angles, $\theta = 0^{o}$ and 90^{o}:

$$\frac{d\sigma}{d\Omega} = \langle f|W|i\rangle \frac{k^2}{(2\pi\hbar)^2}\frac{1}{vc} \quad , \tag{3}$$

where i, f – distorted and bound waves generated in a folding-potential (2); c- velocity of photon, v-velocity of protons, k- wave number of proton.

The operator of electromagnetic field for E1- transition is:

$$W = \left(\frac{2\pi\hbar c}{k}\right)^{1/2} \sum_{m} (-i)(6\pi)^{1/2} D^{*}_{1m}(0,\theta,0) T_{1m}{}^{E^{*}}(k), \tag{4}$$

where, $T^{E}_{1m}(k)$, Q^{E}_{1m} the standard operators in long-wave approximation:

$$T^{E}_{1m}(k) = -\sqrt{2}\frac{k}{3}Q^{E}_{1m}, \quad Q^{E}_{1m} = \int \vec{r} Y_{1m}(\vec{r})\rho(\vec{r})d\vec{r}\,. \tag{5}$$

The spectroscopic factor for joining of proton to ^{16}O nucleus was fixed equal to one. As a whole, calculations reproduce the available experimental data in the energy range (500 – 2500) keV [1], and are in the reasonable agreement with calculations performed with the standard folding potential from the work [2].

Calculation of thermonuclear reaction rates

We have calculated reaction rates of the (p+^{16}O→^{17}F+γ) process by averaging on Maxwell's velocity distribution of protons. Such process takes place at stationary burning in entrails of the sun and stars.

The calculations are based on the data about cross-sections of the reaction at different values of proton energy, reduced in the works [1, 2]. For calculations of reaction rates it is necessary to extrapolate these data on all energy spectrum. But because the cross section at small energies behaves irregularly, its direct extrapolation leads to large errors, therefore it is accepted to extrapolate the S-factor, smoother function, bound up with the cross-section by the ratio:

$$S = \frac{\sigma E_{c.m.}}{P}\,. \tag{6}$$

Here P is the penetrability of the potential barrier, which it is customary, as well as the cross-section, fast descends at decreasing energy. It, purely, also causes smoothness of dependence of the S-factor on energy, providing accuracy of its extrapolation.

There are some computational methods for calculation the penetrability P. Our calculations were conducted in two models: giving exact Coulomb and Gamov penetrability's.

The exact Coulomb penetrability is calculated by the formula:

$$P_l^{ex} = \left[\frac{kr}{F_l^2 + G_l^2}\right]_{r=R}, \tag{7}$$

where R – a channel radius, which is a parameter of the theory, k - a wave vector in a centre-of-mass system, F_l and G_l-regular and non-regular Coulomb wave functions dependent on arguments (ρ=kr and η Coulomb parameter). To calculate ρ and η the following formulae is used:

$$\rho = 0.2187R\left(AE_{c.m.}\right)^{1/2}$$
$$\eta = 0.15748Z_1Z_2\left(A/E_{c.m.}\right)^{1/2}, \qquad (8)$$

where A- a reduced mass in amu, in the given channel.

Gamov's penetrability:

$$P_G = \exp\left\{-2\frac{\sqrt{2\mu}}{\hbar}\frac{\gamma}{\sqrt{E}}\frac{\pi}{2}\right\}, \qquad (9)$$

which is a particular case of the WKB penetrability:

$$P^{WKB} = \exp\left\{-\frac{2\sqrt{2\mu}}{\hbar}\int_{R_1}^{R_2}\sqrt{U(r)-E_{c.m}}\,dr\right\}, \qquad (10)$$ where

$$U(r) = U_{Coul} = \frac{\gamma}{r},\ \gamma = Z_1Z_2e^2,\ R_1 = 0,\ R_2 = \gamma/E. \qquad (11)$$

Results of S-factor calculation with Gamov's penetrability is presented in **Fig. 3**. Calculations are based on experimental and theoretical cross sections.

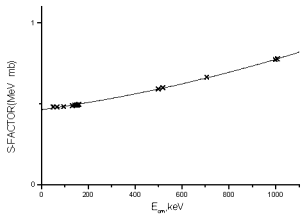


Fig. 3 S-factor of (p+^{16}O→ ^{17}F+γ) process (DC → g. s.) at zero energy range.

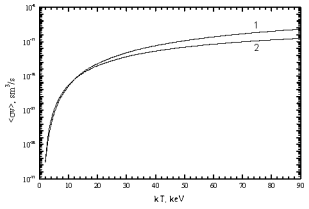


Fig. 4 Maxwell's averaging reaction rates of the (^{16}O(p,γ)^{17}F)-process (DC → g. s.), calculated with Gamov's penetrability.

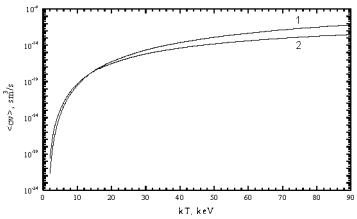


Fig. 5 Maxwell's averaging reaction rates of the ^{16}O(p,γ)^{17}F process (DC → g. s.),, calculated with Coulomb's penetrability.

Parabolic extrapolation of S-factor to zero energy range gives value S(0)=0.4646, which agrees with value S(0)=0.43333 (the work [5]).

An average on maxwellian distribution for the reaction rates in a laboratory system was calculated by the formula:

$$\langle\sigma v\rangle = \left(\frac{8}{\pi}\right)^{1/2}\left(\frac{\mu}{\kappa T}\right)^{3/2}\frac{1}{m^2}\int_0^{\infty} e^{-\frac{\mu E}{m\kappa T}}\sigma(E)EdE. \qquad (12)$$

The numerical integration is carried out from E_{min} up to E_{max} and the lower relation of an integral to these limits is considered.

In **Fig. 4, 5** the results of the average cross sections, obtained by us with the Gamov's penetrability - $\langle\sigma v\rangle_1$ (curve 1 in Fig. 2) and Coulomb's penetrability - $\langle\sigma v\rangle_3$ (curves 1 in Fig. 3) (radius of the channel - 5 fm) and a comparison them with calculated ones earlier in the work [17] - $\langle\sigma v\rangle_2$, $\langle\sigma v\rangle_4$ (curves 2 in Fig. 2, 3) are presented. Our calculation differs from results of the work [17] (the

integrating energy range is in an integral (12)). The integrating was conducted by us in the range ($E_{,min}$=0.001, E_{max} =5 MeV), in the work [17] - in the interval E_{min} = 0.05, E_{max} =1.2 MeV. As it is seen from figures, a difference is not enough at small kT, and starts to be exhibited at kT > 20-30. It is conditioned by sharp exponential relation of distribution in the field of small energies ((0.001-0.05) MeV) and sharp response of an integral to same range, which actuates $<\sigma v>_1$ $<\sigma v>_3$ and does not actuate $<\sigma v>_2$ $<\sigma v>_4$.

Conclusion

As a result of measurements and processing of experimental data there were obtained values of differential cross sections of direct radiative capture (DC → 494 keV) of the reaction $^{16}O(p,\gamma)^{17}F$ in all an angle range. For the angle 135° data were obtained for the first time. Obtained experimental data are in the agreement with data work [1]. The computational method, used by us, of differential radiative capture (DC → g. s.) cross section with using of a cluster folding-potential has allowed to describe correctly available experimental data. Obtained differential cross sections agree with experimental ones. The calculated averaged reaction rates (DC → g. s.) has shown their large sensitivity to low energy range of Maxwellian distribution, or to low limit of integrating. The value of S(0), obtained by us, is equal to 0.4646 and is agreed with the value 0.433 from the work [5].

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