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THE TOTAL NEUTRON CROSS SECTIONS FOR THE N, O, Al, AND Si ELEMENTS AT THE ENERGY OF 14.1 MeV*

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The total neutron cross sections for nitrogen, oxygen, aluminum, and silicon of natural isotopic composition were measured at the energy of $E_n = 14.1$ MeV. The measurements are the continuation of the previous study using a new simple method based on the NG-150 neutron generator of the INP AS, Uzbekistan. The obtained values are in good agreement with the literature data at the nearby energies. These and the published experimental $\sigma_{\rm tot}$, as well as the available data on the elastic neutron scattering, were used to specify the parameters of the phenomenological optical $n+A$ potentials, which are now in demand for calculations of cross sections of nuclear-astrophysical processes involving light nuclei.

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1. Introduction

Experimental data on micro- and macroscopic neutron cross sections are necessary in reactor engineering, in nuclear technologies, for the thermonuclear energy, *etc.* The values of the total cross section (TCS), $\sigma_{\rm tot}$, serve for the correct choice of the parameters of the optical model potential (OMP) for the $n + A$ interaction. In particular, the reasonable values of the OMP parameters are in demand for calculating the cross sections of the nuclear astrophysical processes with light nuclei [1, 2], since the needed values (such as asymptotic normalization coefficients) are conveniently obtained from the analysis of the $A(n, d)$ reactions.

An adequate "individual" phenomenological OMP should reproduce the experimental observables (differential cross section (DCS) of elastic scattering, analyzing power, TCS) for a concrete reaction at the fixed incident

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energy [3]. At the a local OMP describing a specific reaction in a certain energy range and a global OMP suitable for a certain range of nuclear masses in a certain energy domain are based on an "individual" OMP, and cannot reproduce experimental observables just as accurately [3–5].

The aim of this work was to measure the TCS values of neutron interactions with a number of light nuclei at an energy of 14 MeV, and to use them and the literature data on elastic neutron scattering to refine the corresponding OMP parameters.

The dependence of the experimental and calculated values of the neutron TCSs, $\sigma_{\rm tot}$, on the neutron energy is shown in Fig. 1 in the range of 10 keV–250 MeV for a number of light nuclei [3]. It can be seen that at energies > 10 MeV, the energy structure is smoothed out, and the value of TCS becomes a good criterion for selecting OMP.

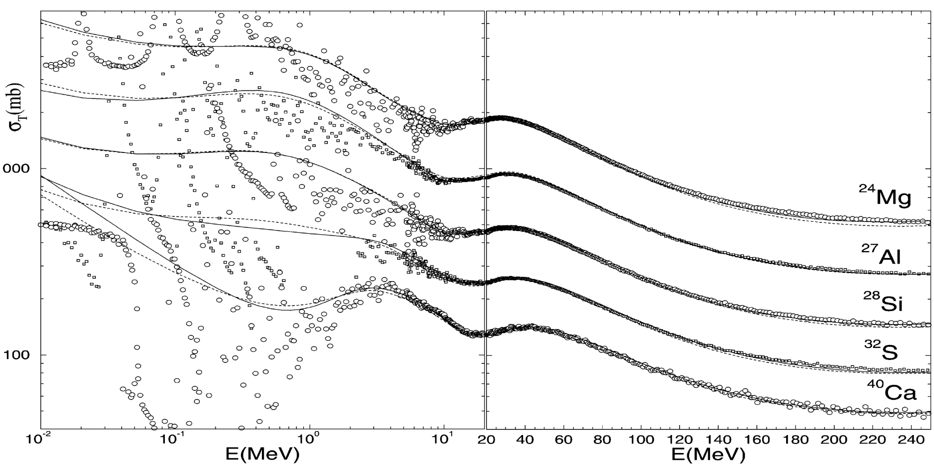

Fig. 1. The energy dependence of the experimental (points) and calculated (curves) total neutron cross sections on energy [3].

2. Experiment

A TCS is usually measured by the well-known transmission method through the attenuation of the neutron flux $\varPhi_0$ in a target (see, for example, [6]). The transmission formula for a complex target with a thickness x containing several chemical elements with different concentrations of n_i has the form of

$$T = \frac{\varPhi(x)}{\varPhi_0} = \exp\left[-x\left(\sigma_1 n_1 + \sigma_2 n_2 + \ldots + \sigma_i n_i\right)\right] , \tag{1}$$

where $\Phi(x)$ is the neutron flux behind a target. But a monoenergetic neutron flux should be used and only those neutrons that did not interact with the target should be registered. That is why the rather complicated methods of neutron detection are often used, such as the time-of-flight method [6].

Earlier, we measured the values of neutron TCS on the nuclei of a number of elements, using a new version of the transmission method developed by us [7]. In this work, the measurements using this technique were performed on the nuclei of the N, O, Al, and Si elements.

The principal scheme of this method using semiconductor Si detectors for neutron registration is shown in Fig. 2. When a neutron interacts with the detector material, the dominant process in this energy range is the $^{28}\mathrm{Si}(n,\alpha_0)^{25}\mathrm{Mg}_{\mathrm{gs}}$ reaction (see the selected peak in the spectrum, inserted in Fig. 2). The area of the corresponding peak in the spectrum recorded by the detector itself is proportional to the neutron flux. Measurements are carried out with and without a target. The primary neutron flux is monitored by another (monitor) silicon detector. The expression for transition value T, in this case, takes the form: $T = N_x/N_0 \times N_{0M}/N_{xM}$ [7], where N_x and N_{xM} are the areas of the (n,α_0) peaks in the spectra of the main and monitor detectors at measuring with a target, and N_0 and N_{0M} are the same for the measurement without a target. This method and measurement procedure are described in more detail in [7].

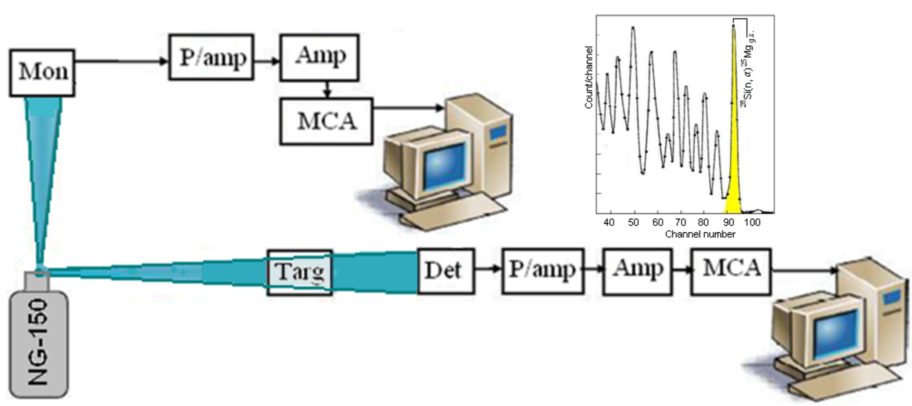

Fig. 2. Scheme of measurement.

The targets were made of chemically pure substances with natural isotope content. Their sizes (lengths $\sim$ 50–100 mm with the diameter $\varnothing$ 22–30 mm) were chosen taking into account the experiment geometry and the restriction on the mass thickness to avoid the effects of multiple interaction of neutrons with the target material. The aluminum and silicon targets were made of metallic aluminum and pure monocrystalline silicon. The nitrogen targets were melamine ($C_3H_6N_6$) or liquid nitrogen (LN_2), and the oxygen target was distilled water. The last two were placed in special thin-walled containers, the absorption in which was measured separately.

The values of TCS measured here and previously [7] as well as the available literature data are presented in Table I. These data and the available literature data on elastic neutron scattering were used to refine the parameters of the optical $n + A$ potentials.

TABLE I

Comparisons of measured here (see also [7]) and literary total cross sections.

Element	Sample	Density [gr/cm^3]	$\sigma_{\rm tot}$ [barn]	$\sigma_{\rm tot}^{\rm lit}$ [barn]	
C	Graphite	2.250	1.430 ± 0.10	1.300 ± 0.06	[8]
N	Melamine ($C_3H_6N_6$)	1.127	1.520 ± 0.05*	1.572 ± 0.01	[9]
	Liquid nitrogen (LN_2)	0.808			
O	Distilled water (H_2O)	1.060	1.565 ± 0.04	1.594 ± 0.03	[10]
Al	^{27}Al (chemically pure)	2.700	1.750 ± 0.09	1.723 ± 0.01	[8]
Si	Monocrystalline silicon	2.330	1.760 ± 0.05	1.790 ± 0.01	[8]

*averaged value

3. Data analysis

The OP for $A + n$ interaction (neglecting the imaginary component of the spin-orbit interaction) can be written in the form of

$$\begin{aligned} U(r) \;=\; & V_V f(r, r_V, a_V) + iW_V f(r, r_W, a_W) + iW_D a_D \frac{\mathrm{d}}{\mathrm{d}r}\left[f(r, r_D, a_D)\right] \\ & + V_{\rm SO}\left(\frac{\hbar}{m_\pi c}\right)^2 \frac{1}{r}\frac{\mathrm{d}}{\mathrm{d}r}\left[f(r, r_{\rm SO}, a_{\rm SO})\right] , \end{aligned} \tag{2}$$

where the form factors are taken in a Woods–Saxon form: $f(r, r_i, a_i) = (1 + \exp\left[(r - R_i)/a_i\right])^{-1}$; $R_i = r_i A^{1/3}$ and a_i are the radii and diffusenesses, respectively. Only the surface form of the imaginary potential was used.

When fitting a set of OMP parameters, we took into account the following four criteria [3]:

(i) the parameter values are physically reasonable, *i.e.* they are in the range corresponding to the general properties of nuclei and microscopic calculations;

(ii) the parameters satisfy the best fit of the calculation to the experimental DCS according to the criterion of the minimum value χ^2;

(iii) accordance in the phases of the oscillations in the experimental angular distribution and a good visual description of the experimental DCS;

(iv) coincidence of the experimental and calculated values of the TCS within the experimental errors.

The OMP parameters from the original papers on elastic neutron scattering or global OMP parameters were used as starting values, and then the depths and geometrical parameters of the real and imaginary parts of the central nuclear potential were varied. In some cases, the starting parameters were adjusted "manually" to obtain the correct TCS value while achieving a good description of the experimental angular distributions of elastic scattering in the subsequent fitting. The parameters were varied in accordance with the χ^2 criterion using the NRV (Nuclear Reaction Video) program [15]. The OMP sets for the considered nuclei obtained in this way together with starting sets, as well as χ^2 values and calculated TCS values are shown in Table II. The first reference in the last column indicates the work from which the experimental data on elastic scattering were taken, the second one — where the starting parameters of the OMP were taken from.

TABLE II

Starting and final sets of the OMP. The subscripts "s" and "f" in the second column indicate the starting and final sets of the OMP parameters for each element.

A	Set	V_V [MeV]	r_V [fm]	a_V [fm]	W_D [MeV]	r_D [fm]	a_D [fm]	$V_{\rm SO}$ [MeV]	$a_{\rm SO}$ [fm]	$r_{\rm SO}$ [fm]	$\sigma_{\rm tot}^{\rm calc}$ [barn]	$\frac{\chi^2}{N_{\rm exp}}$	Ref. DCS	Ref. OMP
C	$\mathrm{C_s}$	−44.86	1.348	0.500	−14.66	1.353	0.200	−5.500	1.150	0.500	1.394	66.08	[11]	[11]
	$\mathrm{C_f}$	−46.87	1.265	0.360	−14.25	1.430	0.138	−5.707	1.285	0.450	1.368	22.23		
N	$\mathrm{N_s}$	−50.22	1.220	0.660	−17.65	1.450	0.130	−5.500	1.150	0.500	1.500	7.89	[12]	[12]
	$\mathrm{N_f}$	−49.84	1.218	0.671	−16.79	1.465	0.125	−4.397	1.140	0.528	1.560	7.01		
O	$\mathrm{O_s}$	−44.86	1.295	0.500	−14.66	1.353	0.200	−5.500	1.150	0.500	1.405	33.65	[11]	[11]
	$\mathrm{O_f}$	−45.75	1.283	0.633	−13.17	1.403	0.211	−4.933	1.669	0.568	1.577	10.23		
Al	$\mathrm{Al_s}$	−48.91	1.169	0.674	−7.403	1.295	0.540	−5.444	0.790	0.590	1.761	22.45	[13]	[3]
	$\mathrm{Al_f}$	−57.34	1.122	0.664	−7.652	1.300	0.551	−8.780	0.763	0.679	1.739	2.57		
Si	$\mathrm{Si_s}$	−49.54	1.170	0.674	−7.685	1.294	0.540	−5.445	0.795	0.590	1.782	14.13	[14]	[3]
	$\mathrm{Si_f}$	−52.58	1.159	0.631	−8.400	1.315	0.552	−5.553	0.898	0.550	1.775	8.26		

In Fig. 3, the experimental and calculated (with starting and final sets of OMP) angular distributions of neutron scattering are displayed. One can see the fine description of the experimental data at using the OMP parameters obtained by the method proposed above.

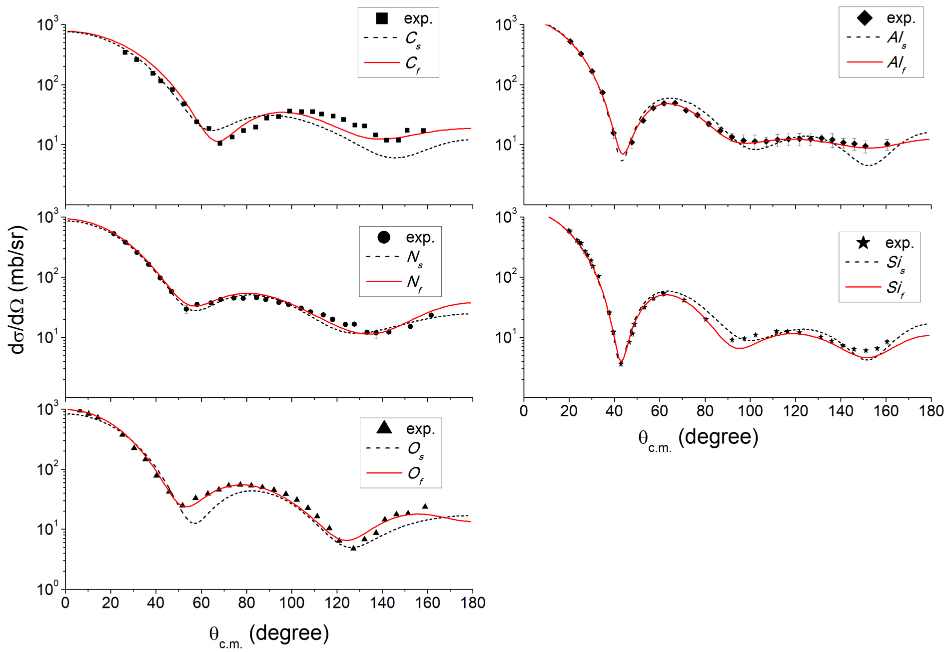

Fig. 3. The experimental and calculated (with starting and final sets of OMP) angular distributions of neutron scattering.

4. Conclusion

The natural content of the main isotopes (^{12}C, ^{14}N, ^{16}O) is more than 99%, and the content of ^{28}Si and ^{32}S is 92.2% and 95.0%, respectively. Taking into account the smooth dependence of the OMP parameters on the mass number A and neutron energy (predicted by the global and semimicroscopic potentials [16]), we assume that in all considered cases the found sets of OMP will also adequately describe the elastic neutron scattering, reaction, and total cross sections for the mentioned above main isotopes.

The obtained OMP potentials will be used in the analysis of the proton transfer reactions $B(n,d)A$ and $A(d,n)B$ to extract the ANC values of the bound states of the proton $B \to A + p$. The ANC values are needed in the planned extrapolation calculations of astrophysical S-factors of radiative proton capture by the considered light nuclei.

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