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# SELECTED ARTICLES TRANSLATED FROM JADERNYE KONSTANTY (NUCLEAR CONSTANTS) VOLUMES 3 - 4, 1994



Translated by the IAEA

June 1997

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# SELECTED ARTICLES TRANSLATED FROM JADERNYE KONSTANTY (NUCLEAR CONSTANTS) VOLUMES 3 - 4, 1994

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## CONTENTS

95-11660 (33 + H)
Translated from Russian

# MEASUREMENT OF THE EXCITATION FUNCTIONS OF THE REACTIONS $^{27}Al(^{3}He,X)^{24,22}Na$ AT ENERGIES UP TO 90 MeV

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The cross-sections of the reactions $^{27}Al(^{3}He,X)^{24,22}Na$ were measured by the method of induced gamma activity in foil in the energy region 18-91 MeV. The $^{3}He$ ion source was a U-240 cyclotron and the ion energy spread was ~ 0.5 MeV. Gamma radiation was measured with a Ge detector with a resolution of 2.4 keV at $E_\gamma$ = 1.3 MeV. The cross-section errors contain statistical and systematic components. The measured cross-sections are compared with data from two works in the region below 40 MeV.

The excitation functions of nuclear reactions producing nuclides from the interaction of charged particles with aluminium are required for the development of nuclear technology and also for carrying out nuclear physics experiments. In particular, when measuring the reaction cross-sections for the formation of radionuclides by the foil stack method, aluminium foils are normally employed to reduce the beam energy, and the excitation functions of the reactions for the formation of the radionuclides $^{24,22}Na$ are used both for absolutizing the cross-sections and for determining the beam energy.

As opposed to the reactions with protons, deuterons and alpha particles, for which the cross-sections for the formation of the radionuclides $^{24,22}Na$ on aluminium are measured quite accurately and in a wide range of energies, in the case of $^{3}He$ particles the experimental cross-sections of these reactions exist in the main only in the energy region up to 36 MeV [1-3]. At higher energies of $^{3}He$ only one experiment has been performed [3], in which the excitation functions of the above reactions were measured with quite a large interval

(16 experimental points in the energy range 40-126 MeV). In the work reported here the cross-sections of the reactions $^{27}Al(^{3}He,X)^{24,22}Na$ were measured in the range up to 91 MeV at 40 energy values.

## EXPERIMENT

To determine the cross-sections, aluminium foils were used which were employed as absorbers during irradiation of four target stacks with $^{3}He$ ions from the Kiev U-240 cyclotron accelerated to energy $E_0$ = 93 MeV. The initial energy spread of the beam was less than 0.5 MeV. The induced gamma activity was measured for each foil. The measurements were performed with a detector made of ultrapure germanium with a recording efficiency of 50% and an energy resolution of 2.4 keV at $E_\gamma$ = 1.3 MeV. The foils had a thickness from 52.0 to 12.4 $mg \cdot cm^{-2}$. A detailed description of the methods used here for irradiating the targets, measuring the beam current and measuring the gamma spectra, as well as formulae for determining the reaction cross-sections from the induced activity values are given in Ref. [4]. The half-lives of the radionuclides $T_{1/2}$, energies $E_\gamma$ and the quantum yields $I_\gamma$ of the gamma peaks used for determining the cross-sections were taken from handbooks, $T_{1/2}$ from Ref. [5] and $E_\gamma$ and $I_\gamma$ from Ref. [6].

## EXPERIMENTAL RESULTS

The experimental values of the cross-sections are given in Table 1 and Fig. 1. For comparison, data from Refs [1-3] are shown in the figure. The cross-section errors shown in the table include both statistical and systematic errors apart from the error in measuring the beam current $\Delta\Phi$. In order to reduce $\Delta\Phi$, a calibrating experiment was performed: on a rig with an accurate beam monitoring system [7] separate targets consisting of the same elements as the targets in the stacks were irradiated, and from the measured induced activities of these targets the reaction cross-sections were determined. The cross-sections measured in the experiments with target stacks were multiplied by a single correction coefficient, obtained by aligning these cross-sections with the cross-sections measured in the calibrating experiment. The error $\Delta\Phi$ amounts to less than 10%. For calculating the beam energies in the target stacks, the energy $E_0$ was varied in the limits of error of its determination $\Delta E_0$ = 2 MeV and corrected values of $E_0$ were chosen corresponding to the best fit of the excitation functions for $^{24}Na$ to the data in Ref. [1]. The corrected values of $E_0$ were 92.5 MeV for the three stacks irradiated in one series of experiments, and 93.5 MeV for the stack irradiated in another series. For calculating the energies, the mass stopping powers of $^{3}He$ ions in matter given in Ref. [8] were employed. The experimental cross-sections obtained from measuring aluminium foils irradiated in different target stacks were averaged, if the calculated values of the mean beam energies on these foils differed by less than 1 MeV. The energy errors shown in the table correspond to the variation of the beam energy on passage through the target without allowance for its energy spread.

As can be seen from the figure, the results of our experiment are in good agreement with data obtained in other laboratories. The systematic deviations observed between the cross-sections measured by us and data obtained by Mishel' et al. [3] amount on average to 12% for $^{24}Na$ and 5% for $^{22}Na$ which is less than the systematic errors of these cross-sections. Thus the experimental data reported in Refs [1-3] combined with those obtained here make it possible to obtain evaluated cross-sections of the reactions $^{27}Al$ ($^{3}He$,X)$^{24,22}Na$ in the range of energies of $^{3}He$ up to 100 MeV with an accuracy on average no worse than 5-7%, and these data can be used in monitoring experiments.

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TABLE 1. CROSS-SECTIONS OF THE REACTIONS $^{27}Al(^{3}He,X)^{24,22}Na$

| E, MeV | σ, mb | | E, MeV | σ, mb | |
|---|---|---|---|---|---|
| | $^{24}Na$ | $^{22}Na$ | | $^{24}Na$ | $^{22}Na$ |
| 90,7(16) | 23,0(17) | 46,4(34) | 47,0(7) | 32,1(32) | 11.9(12) |
| 88,1(17) | 23,7(17) | 51,9(37) | 45,4(19) | 38,2(39) | 12,2(13) |
| 86,4(15) | 28,9(29) | 45,8(47) | 43,9(21) | 37,2(27) | 10,8(8) |
| 85,1(4) | 21,9(22) | 58,0(58) | 41,1(6) | - | 9,4(10) |
| 82,8(16) | 23,6(17) | 53,9(38) | 40,4(23) | 42,3(30) | - |
| 81,4(16) | 25,3(26) | 50,9(52) | 38,1(7) | - | 9.5(10) |
| 79,6(4) | 26,3(26) | 57,4(58) | 37,6(7) | 42,0(42) | - |
| 77,4(16) | 21,1(21) | 49,8(50) | 36,6(14) | 36.7(35) | 10,1(10) |
| 76,5(18) | 23,5(17) | 49,3(35) | 34,6(19) | 35,7(26) | 12,2(12) |
| 73,8(4) | 26,0(26) | 55,0(55) | 31,1(8) | - | 16,2(16) |
| 71,3(19) | 23,0(13) | 47,1(28) | 29,9(19) | 23,0(17) | - |
| 67,7(4) | 26,5(27) | 50,6(51) | 28,9(18) | 15,9(16) | 24,0(24) |
| 66,5(19) | 23,4(24) | 42,6(44) | 27,1(9) | - | 25,3(26) |
| 64,6(20) | 23,6(17) | 44,9(32) | 26,2(9) | 5,0(5) | - |
| 61,1(21) | 25,6(18) | 36,9(27) | 23,8(22) | 1,66(18) | - |
| 57,7(21) | 25,1(18) | 32,8(23) | 23,3(10) | - | 28,4(29) |
| 55,7(22) | 28,8(29) | 25,1(27) | 22,3(10) | 0,61(7) | - |
| 53,8(5) | 30,3(30) | 23,8(24) | 20,2(11) | 0,32(4) | 23,8(24) |
| 50,6(18) | 31,0(22) | 18,8(14) | 19,1(12) | - | 19,0(19) |
| 49,9(5) | 35,4(36) | 15,1(15) | 18,2(14) | 0,14(5) | - |

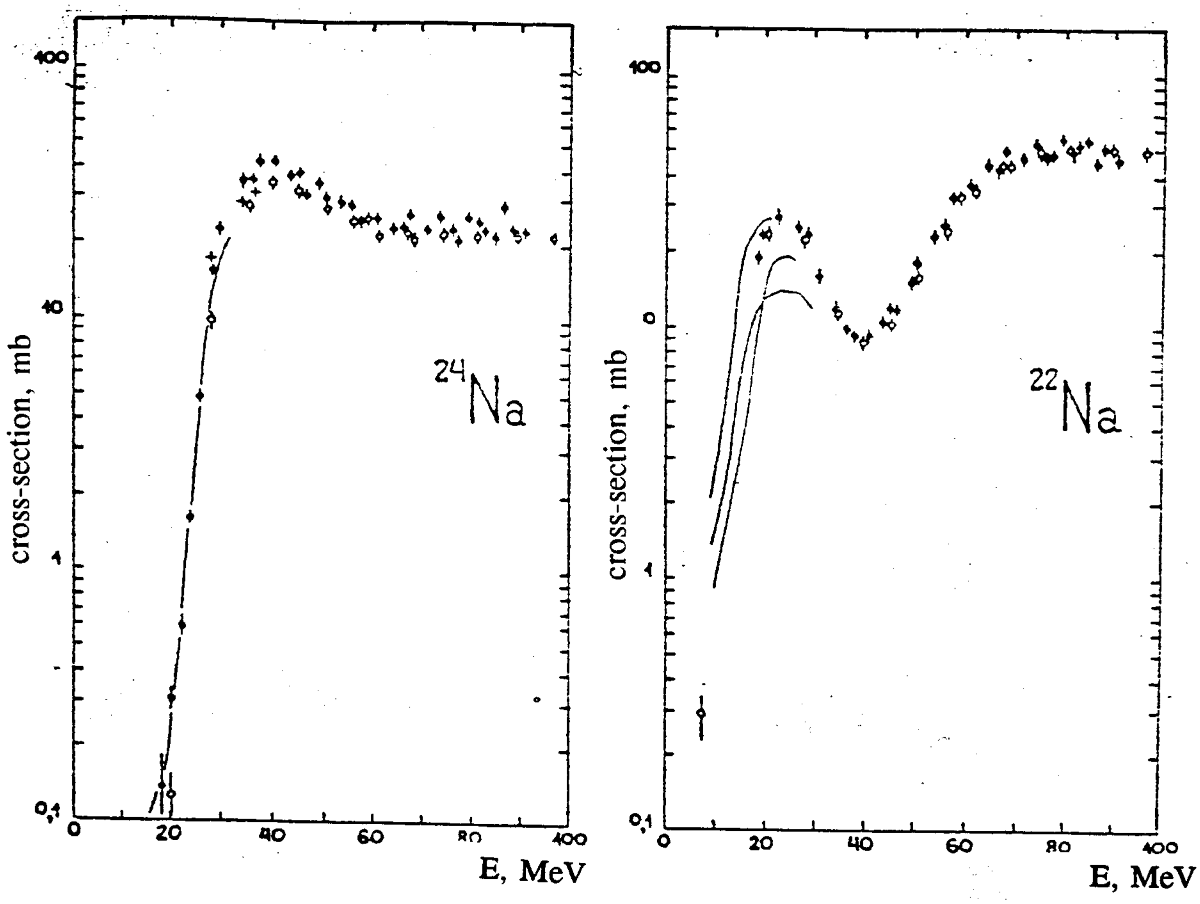


*FIG. 1. Cross-sections of the reactions $^{27}Al(^{3}He,X)^{24,22}Na$. The dots represent data from this work, the curves data from Ref. [1], the plus sign data from Ref. [2], and the noughts data from Ref. [3].*

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# INELASTIC SCATTERING OF 275 keV NEUTRONS BY SILVER

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## ABSTRACT

Neutron total, elastic and inelastic scattering cross-sections of Ag at the $E_n = 275$ keV neutron energy were measured by using the filtered neutron beam of the WWR-M reactor in Kiev. The d-neutron strength function $S_{n2}$ of Ag was determined from the analysis of all available data in the $E_n \leq 600$ keV energy region on neutron inelastic scattering cross-sections with excitation of the first isomeric levels $I_m^\pi = 7/2^+$, $E_m \sim 90$ keV of $^{107,109}$Ag: $S_{n2} = (1.03 \pm 0.19) \cdot 10^{-4}$.

## Introduction

The two stable isotopes of silver $^{107,109}$Ag, which constitute a natural mixture, have very similar systems of lower excited states, including the isomeric state $I_m^\pi = 7/2^+$ which differs strongly with regard to spin from the ground state $I_g^\pi = 1/2^-$ (Fig. 1). As has been shown in Ref. [1], the presence of a low-lying isomeric level means that one can reliably determine the d-neutron strength function $S_{n2}$ from an analysis of the neutron inelastic scattering cross-section $\sigma_{in}^m$ near the excitation threshold of this isomer. In contrast to the s- and p-neutron strength functions, the currently available experimental information on $S_{n2}$ is extremely limited [2]. The conventional method for determining $S_{n2}$ consists in analysing the total neutron cross-sections $\sigma_{tot}$ and the neutron radiative capture cross-sections $\sigma_\gamma$ [3]. As was noted in Ref. [1], a major disadvantage of the conventional approach is the strong correlation between the values of $S_{n2}$ to be determined and the average resonance parameters of the s- and p-partial neutron waves. The method proposed in Ref. [1] for determining $S_{n2}$ from an analysis of $\sigma_{in}^{m}$ does not have this disadvantage; however, for a wide range of nuclei the use of this method is restricted both by the absence of a low-lying isomeric state in the majority of nuclei and the methodological complexity of measuring $\sigma_{in}^{m}$.

Owing to the large difference in spin from the ground state, the low-lying isomeric levels have a comparatively large half-life. As a result, $\sigma_{in}^{m}$ can be measured with the use of the activation method - by producing the isomer in the neutron beam and then measuring discharge photons outside the beam. However, proper account must be taken in this method of a number of corrections (for self-absorption of photons by the sample, conversion decay, etc.) the ambiguity of which may result in a large systematic error in the determination of $\sigma_{in}^{m}$.

Where the difference in the spins of the ground and isomeric states is $\Delta I \geq 3$, the cross-section $\sigma_{in}^{m}$ near the threshold is of the order of tens of millibarns. Since the elastic scattering cross-section $\sigma_{el}$ is ~ 10 b, measurement of $\sigma_{in}^{m}$ by the direct recording of inelastically scattered neutrons is difficult owing to the high elastic scattering background $\sigma_{in}^{m}/\sigma_{el} \leq 10^{-3}$. Also, in Ref. [4] using $^{103}Rh$ as an example, we demonstrated the possibility of measuring $\sigma_{in}^{m}$ near the threshold by direct recording of inelastically scattered neutrons, employing intensive filtered reactor neutron beams (flux at sample location $\Phi \sim 10^{6}$ n/s·cm$^{2}$), to an accuracy of ~ 7 mb.

## Experimental method

The total neutron cross-section $\sigma_{tot}$ was measured by the transmission method; $\sigma_{el}$ and $\sigma_{in}$ were measured by direct recording of elastically and inelastically scattered neutrons. The measurement method for $\sigma_{tot}$, $\sigma_{el}$ and $\sigma_{in}$ has been described in detail in Refs [5, 6]. The beam of quasimonoenergetic neutrons with an average energy of $E_n$ = 275 keV was produced from a reactor beam using an Mn- (thickness 270 g/cm$^2$), V- (50 g/cm$^2$), S- (54 g/cm$^2$) and $^{10}$B-based (0.2 g/cm$^2$) filter placed in the outlet discs of the channel gate [7]. The relative contribution of the group of quasimonoenergetic neutrons with an energy of $E_n$ = 275 keV was 65.4%; the neutron flux at the sample location in the scattering experiment was $\Phi \sim 3 \cdot 10^5$ n/cm$^2$. In the transmission and scattering experiments, we used an elliptical metallic Ag sample (weight 110.06 g, thickness 2.92 mm, semiminor axis 29.32 mm and semimajor axis 38.55 mm). An SNM-38 spectrometric proportional hydrogen counter was used for the neutron recording; in the scattering experiments, this instrument made it possible to separate the groups of elastically and inelastically scattered neutrons. The scattering cross-sections were measured at an angle of $\theta$ = 90°. The method used for processing the primary experimental data and calculating the corrections for multiple processes in the sample has been described in detail in Refs [6, 8].

The values obtained for $\sigma_{tot}$ and $\sigma_{in}^{m} / \sigma_{el}$ at $E_n$ = 275 keV in the present work were:

$$\sigma_{tot} = 7.59 \pm 0.19 \qquad (1)$$

$$\sigma_{in}^{m} / \sigma_{el} = (9.0 \pm 7.6) \cdot 10^{-3}. \qquad (2)$$

The absolute values of $\sigma_{in}^{m}$ and $\sigma_{el}$ were determined by normalizing their sums to the difference between $\sigma_{tot}$ and the neutron radiative capture cross-section $\sigma_\gamma$. The evaluated data from Ref. [9] were used for $\sigma_\gamma$: $\sigma_\gamma$ = 0.30 ± 0.03 b at $E_n$ = 275 keV. The values obtained for $\sigma_{el}$ and $\sigma_{in}^{m}$ were:

$$\sigma_{el} = 7.29 \pm 0.21 \, \text{b} \qquad (3)$$

$$\sigma_{in}^{m} = 65 \pm 55 \, \text{mb}. \qquad (4)$$

**Analysis of the inelastic scattering cross-section**

The data on $\sigma_{in}^{m}$ near the excitation threshold of the isomeric states $I_m^\pi = 7/2^+$ $E_m \sim 90$ keV of the $^{107,109}$Ag nuclei were obtained first. Among the data available in the literature, those for $\sigma_{in}^{m}$ which were closest to the threshold were obtained in Ref. [5] at energies of $E_n = 500$ and 600 keV (Fig. 2). These data, together with the results of the present work, were analysed with a view to determining the d-neutron strength function $S_{n2}$ for Ag.

The parametrization formalism for $\sigma_{in}^{m}$ has been described in detail in Ref. [1]. The inelastic scattering cross-section was parametrized with the help of an expression which takes the form of the well-known Hauser-Feshbach-Moldauer formula:

$$\sigma_{in} = \frac{2\pi^2}{k^2}\sum_{J\pi}\frac{g(J)}{D_J}\sum_{ll'}\frac{\Gamma_n^{jl}\Gamma_{n'}^{jl'}}{\Gamma_J}F, \qquad (5)$$

where $D_J$ is the average distance between resonances with spin J; $\Gamma_j$, $\Gamma_n^{jl}$ and $\Gamma_{n'}^{jl'}$ are the average values of the total resonance width and the partial neutron widths in the elastic and inelastic scattering channels; F is the fluctuation factor. The neutron widths, $\Gamma_n^{jl}$, $\Gamma_{n'}^{jl'}$ were parametrized in terms of the neutron strength functions $S_{nl}$:

$$\Gamma_{n(n')}^{Jl} = \frac{S_{nl}}{d_l}\nu_l D_J n_{Jl}\sqrt{E_{n(n')}}, \qquad (6)$$

where $d_l$ and $\nu_l$ are the renormalization factor and the optical transmission for the neutron wave with the orbital momentum l; $n_{Jl}$ is the degree of degeneracy of the total momentum of the system J; $E_{n(n')}$ is the neutron energy in the elastic (inelastic) scattering channel.

For the calculations, we used the data from Ref. [2] on the average resonance parameters of Ag for the s- and p-partial waves. The contributions of the s-, p-, d- and f-partial neutron waves to $\sigma_{in}^{m}$ for Ag are shown in Fig. 2. It will be seen from the figure that $\sigma_{in}^{m}$ is chiefly sensitive to the d-neutron strength function $S_{n2}$, as is concluded in Ref. [1]. The experimental data in Ref. [5] and in this paper were approximated using the method of least squares by expression (5) with the variation of $S_{n2}$. The result of the approximation is shown in Fig. 2 as a continuous line. The value of $S_{n2}$ obtained is

$$S_{n2} = (1.03 \pm 0.19) \cdot 10^{-4} . \qquad (7)$$

Prior to this paper, there were no experimental data on $S_{n2}$ for Ag. The value obtained for $S_{n2}$, which is shown in expression (7), does not contradict the systematics of the data for neighbouring nuclei [1] (Fig. 3).

In conclusion, it should be noted that the Mn-, V-, S- and $^{10}$B-based neutron filter used in the present work imposes a substantial limitation on the accuracy of the determination of $\sigma_{in}^{m}$ owing to the high admixture of background groups of quasimonoenergetic neutrons (~ 35%). The use of the filter proposed in Ref. [10] for an energy of $E_n$ = 317 keV, which does not have this disadvantage, will evidently ensure a much higher accuracy in subsequent measurements of $\sigma_{in}^{m}$ for a number of nuclei. Promising candidates for the study of the mass dependence of the d-neutron strength function $S_{n2}$ are the $^{77}$Se, $^{79}$Br and $^{189}$Os nuclei, which have relatively low-lying isomeric states and for which there are no data at present on $\sigma_{in}^{m}$.

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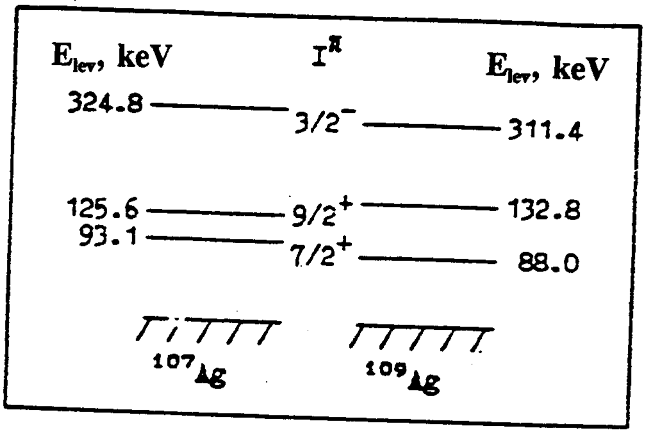


*FIG.1. The lower level schemes for $^{107,109}Ag$.*

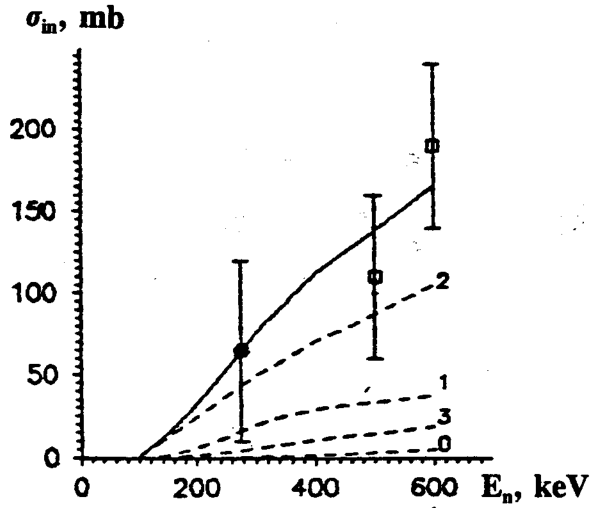


*FIG. 2. Neutron inelastic scattering cross-section for Ag. □ , • - data from Ref. [5] and this paper, respectively. Continuous line - approximation of the experimental data. Dashed lines - partial contributions of the s- (0), p- (1), d- (2) and f- (3) neutron waves.*

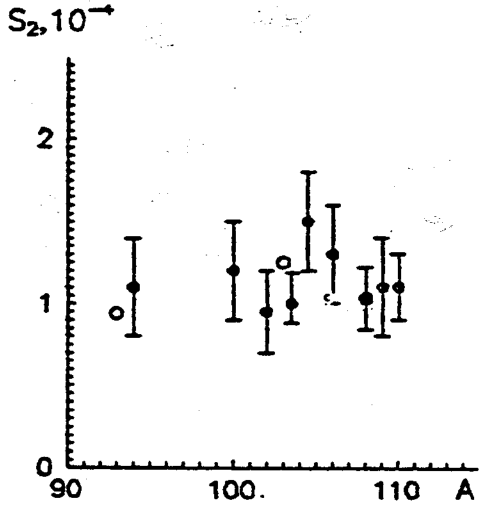


*FIG. 3. Mass dependence of the d-neutron strength function in the $90 \leq A \leq 110$ region [1]. • - result from this paper.*

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# TOTAL NEUTRON CROSS-SECTIONS OF IRON ISOTOPES $^{54,56,57}Fe$ IN THE 3-6000 eV ENERGY REGION

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## ABSTRACT

The total neutron cross-sections $\sigma_{tot}$ of $^{54,56,57}Fe$ were measured in the E = 3-6000 eV energy region by the time-of-flight spectrometer technique in the neutron beam of the Kiev WWR-M reactor. The influence of distant negative resonances on $\sigma_{tot}$ parametrization was investigated and the resonance parameters of $^{54,56,57}Fe$ determined. The potential scattering radii $R_0$ were found to depend strongly on the contributions of the distant negative resonances.

Neutron data for iron isotopes are of undoubted practical interest since this element is the basic construction material used in all nuclear physics and nuclear power facilities. Over the past decade the neutron cross-sections of Fe isotopes in most evaluated neutron data files (ENDF, BNAB, etc.) have been re-evaluated. At the same time, there is practically no reliable experimental information on the total neutron cross-sections $\sigma_{tot}$ of the less common $^{54,57,58}Fe$ isotopes in the E < 10 keV energy range and the experimental data obtained at various laboratories for the main $^{56}Fe$ isotope show a spread of ≥ 10% [1].

As well as being used as construction materials, elements with an intermediate atomic weight $40 < A < 70$ are used to make interference neutron filters and here too reliable experimental information on $\sigma_{tot}$ [2] is required.

Besides the importance of experimental data in resolving applied problems, information on the $\sigma_{tot}$ of intermediate weight nuclei is of interest from the point of view of the systematics of neutron resonance parameters, which are necessary for correct calculation of the neutron cross-sections used in the current models of stellar nucleosynthesis to verify predictions of various versions of the statistical model [4], etc.

Analysis of $\sigma_{tot}$ plays a major role in the selection and refinement of the formalism for neutron cross-section parametrization in the resolved resonance region. For example, our analysis [5] of the total neutron cross-sections for Ni isotopes confirmed the applicability of the simplest multilevel formulae for describing $\sigma_{tot}$ in the minima region. In the same paper it was shown that the total neutron cross-section in the energy region below the first positive resonance ($E < E_1$) displays strong sensitivity to the negative resonance parameters (compound nucleus levels lying below the neutron binding energy). The influence of negative resonances on neutron cross-section parametrization in the $E < E_1$ region for nuclei with an intermediate atomic weight was examined in detail in Ref. [6]. In that paper it was shown that the approach commonly adopted in cross-section parametrization - use of one "effective" negative resonance and neglect of the contributions of distant negative resonances - could lead to appreciable distortion of the potential scattering radius and of the first positive resonance parameters and reduce the quality of cross-section parametrization in the $E < E_1$ region.

The present paper contains the results of total neutron cross-section $\sigma_{tot}$ measurements for the $^{54,56,57}Fe$ isotopes in the E = 3-6000 eV energy range performed by the time-of-flight method on the neutron beam of our Institute's WWR-M reactor. We have given the results of combined analysis of the $\sigma_{tot}$ data obtained and of data [1] on the thermal neutron radiative capture cross-section $\sigma_{\gamma}^{th}$ with a view to determining the effect of resonances on cross-section parametrization.

## Experimental method

The total neutron cross-sections $\sigma_{tot}$ were determined using the transmission method. A detailed description of the experimental method was provided in Refs [5, 7, 8]. The measurements were performed on a neutron spectrometer by the time-of-flight method with a path length of ~ 70 m. The duration of the neutron pulse formed by the mechanical chopper was 5 $\mu$s. To reduce the gamma background and the background due to multiple scattering of fast neutrons, we used a $^{60}$Ni filter ~ 25 g/cm$^2$ thick installed directly behind the mechanical chopper [5]. The neutrons were recorded using a bank of $^3$He counters.

Measurements of $\sigma_{tot}$ were made on metal samples with a high level of enrichment in the isotope under investigation ($\geq$ 95%). The characteristics of the samples are given in Table 1. Corrections for the admixture of other isotopes when determining $\sigma_{tot}$ were calculated by the method of successive approximations on the basis of the experimental data obtained in the present paper for $^{55,56,57}$Fe and the data in Ref. [1] for $^{58}$Fe.

The results of the $\sigma_{tot}$ measurements for $^{54,56,57}$Fe are presented in Figs 1, 2 and 3.

## Neutron cross-section parametrization

The cross-section parametrization formalism used in this paper is similar to that described in Ref. [5]. In the energy range under examination E = 3-6000 eV Doppler broadening for nuclei of intermediate weight A ~ 50-60 is $\Delta$ ~ 2 eV and is considerably less than the neutron widths of s-resonances (the contribution of p-resonances in the range under examination is insignificant). Therefore, no allowance was made for Doppler broadening when analysing the experimental data in the present work. The multilevel Reich-Moore formulae [9] were used to parametrize $\sigma_{tot}$ and $\sigma_\gamma^{th}$:

$$\sigma_{tot} = \sigma_p + 4\pi\lambda^2 \sum_{J\pi l} g(J) \frac{A_{J\pi}^2 + B_{J\pi}^2 + B_{J\pi})\cos(2\varphi_l) - A_{J\pi}\sin(2\varphi_l)}{A_{J\pi}^2 + (1 + B_{J\pi})^2}, \quad (1)$$

$$\sigma_\gamma = 4\pi\lambda^2 \sum_{J\pi l} g(J) \frac{B_{J\pi}}{A_{J\pi}^2 + (1 + B_{J\pi})^2}, \quad (2)$$

where $\sigma_p$ is the potential scattering cross-section:

$$\sigma_p = 4\pi\lambda^2 \sum_{J\pi l} g(J) \sin^2(\varphi_l), \quad (3)$$

$A_{J\pi}$ and $B_{J\pi}$ are the real and imaginary parts of the R-matrix, the elements of which are defined in the form:

$$R_{J\pi} = A_{J\pi} + iB_{J\pi} = \frac{1}{2} \sum_{\lambda(J\pi)} \frac{\Gamma_{\lambda n}}{E_\lambda - E - i\Gamma_{\lambda\gamma}/2}, \quad (4)$$

where $E_\lambda$ is the energy of the $\lambda$-th resonance and $\Gamma_{\lambda n}$, $\Gamma_{\lambda\gamma}$ are its neutron and radiation widths. Resonances (including the negative resonances) from the limited energy range $\Delta E$ make a contribution to the summation in $\lambda$ in Eq. 4. Correct parametrization requires that this range includes a sufficiently large number of resonances on both sides of point E on the energy scale and that it is approximately symmetrical, thereby fulfilling the conditions:

$$\Delta E >> \langle D \rangle, \quad (5)$$

$$|E_{\lambda_{min}} - E| \approx |E_{\lambda_{max}} - E|, \quad (6)$$

where $<D>$ is the average distance between resonances as observed in the "resolved" region; $E_{\lambda min}$, $E_{\lambda max}$ are the minimum and maximum resonance energies considered in the summation in Eq. (4).

The contribution of distant resonances beyond the range [$E_{\lambda min}$, $E_{\lambda max}$] is taken into account in the form of the background part of the R-matrix, the elements of which are called potential scattering parameters $R_l^\infty$. A zero value of parameters $R_l^\infty$ leads to the renormalization of the potential scattering phases $\varphi_l$ with respect to the optical phases $w_l$ corresponding to scattering on an impenetrable sphere with a radius equal to that of the nucleus [10]:

$$\varphi_0 = w_0 - \mathrm{arctg}(k\,\alpha\,R_0^\infty)\,,\ \ w_0 = k\,\alpha\,, \tag{7}$$

$$\varphi_1 = w_1 - \mathrm{arctg}\frac{(k\,\alpha)^3 R_1^\infty}{1 + (k\,\alpha)^2 + R_1^\infty}\,,\ \ w_1 = k\,\alpha - \mathrm{arctg}(k\,\alpha)\,, \tag{8}$$

where $\alpha$ is taken to be $\alpha = 1.35A^{1/3}$ [Fermi].

The potential scattering radius of the s-neutrons $R_0^{'}$ used in practical applications connected with the parameter $R_0^\infty$ by an expression of the form:

$$R_0^{'} = \alpha\,(1 - R_0^\infty)\,. \tag{9}$$

As pointed out above, the commonly adopted approach to cross-section parametrization consists in using one (less often two or three) "effective" negative resonance. This approach is justified when analysing data at a neutron energy $E >> 0$, when to the left of the analysed sector there are a sufficiently large number of positive resonances to be considered. When parametrizing cross-sections in the energy range below the first positive resonance, the conventional approach leads to violation of conditions (5) and (6), involving redefinition of the first positive resonance parameters and $R_0^\infty$ [6]. For this reason, in the present paper cross-section parametrization was carried out in two versions: one using the conventional approach with one "effective" negative resonance; and the other using the method described in Ref. [6] in which account was taken of distant negative resonances in the form of an equidistant "palisade". In the latter case the contribution of ten negative s-resonances were taken into consideration in addition to the first negative resonance. The following energies were assigned to the additional negative resonances with spin J:

$$E_{(-i)} = E_1 - i\langle D_J\rangle \ , \ \ i = 2\div 11 \ , \tag{10}$$

where $\langle D_J\rangle = \langle D\rangle / g(J)$; $E_1$ is the energy of the first positive resonance.

The reduced neutron widths of the additional negative resonances

were taken to be equal to:

$$\Gamma^0_{(-i)n} = \Gamma_{(-i)n}/\sqrt{E} \tag{11}$$

$$\Gamma_{(-i)n} = \langle D_J\rangle\ S_{n0}\ , \tag{12}$$

where $S_{n0}$ is the s-neutron strength function.

In the case of $^{57}Fe$, whose s-resonance spins can take two values J = 0 and 1, five additional negative resonances were taken into account for each value of J in the calculation.

The radiation widths $\Gamma_{\lambda\gamma}$ of nuclei with an intermediate atomic weight fluctuate little from resonance to resonance [1]. Therefore, for all the negative resonances considered the $\Gamma_{(-i)\gamma}$ values were taken to be equal to the average radiation width $\langle\Gamma_\gamma\rangle$ for the given nucleus:

$$\Gamma_{(-i)\gamma_i} = \langle\Gamma_\gamma\rangle\ . \tag{15}$$

The $S_{n0}$, $<D>$ and $<\Gamma_{\gamma}>$ values used in the calculations were taken from Ref. [1]. For the parameters of the distant positive resonances lying above the range under examination E = 3-6000 eV we used data from Ref. [1] and the BNAB-2 and TNDF/B-V libraries. Analysis showed a weak sensitivity to small (10-20%) variations in these parameters.

The experimental data for $\sigma_{tot}$ and $\sigma_{\gamma}^{th}$ were approximated, with the use of the least squares method, by expressions (1) and (2) with variation of the parameters of the first positive resonance (in the case of $^{54,57}Fe$), the first negative resonance ($^{54,56}Fe$) and the potential scattering parameter $R_0^{\infty}$ ($^{56,57}Fe$).

**Results and discussion**

The results of approximating the $\sigma_{\gamma}^{th}$ and $\sigma_{tot}$ data for $^{54,56,57}Fe$ are presented in Table 2 and Figs 1, 2 and 3.

For $^{54,56}Fe$ the calculated cross-section values and the quality of parametrization of the experimental data ($\chi^2$-criterion) were close in both calculation versions - with and without allowance for distant negative resonances.

Table 3 gives the parameters of the first negative and positive $^{54}Fe$ resonances obtained in the two calculation versions in comparison with the data in Ref. [1]. As can be seen from the table, the experimental data show the greatest sensitivity to the radiation width of the first positive resonance $\Gamma_{1\gamma}$. The value obtained for $\Gamma_{1\gamma}$ agrees satisfactorily with the data of the review contained in Ref. [1] and has a substantially higher accuracy.

In Table 4 we compare the $^{56}Fe$ resonance parameters obtained in the present work with the data in Ref. [1]. As can be seen from the table, the value of the potential scattering radius $R_0^{'}$ obtained by calculation with allowance for the contribution of distant negative resonances shows better agreement with the data in Ref. [1] compared with the calculation using the conventional approach (with one "effective" negative resonance).

Parametrization of the $^{57}Fe$ cross-sections in both calculation versions did not require the introduction of the first negative resonance. In both cases taking it into account did not improve the $\chi^2$-criterion of parametrization, and the neutron width of the first negative resonance $\Gamma^{o}_{(-1)n}$ determined by the least-squares method was close to zero. For the two calculation versions the value of the $\chi^2$-criterion was:

$\chi^2 = 7.5$ - without allowance for the contribution of distant negative resonances (16)

$\chi^2 = 7.1$ - with allowance for the contribution of distant negative resonances

The values obtained using the two calculation versions for the parameters of the first positive resonance and the potential scattering radius $R_0'$ for $^{57}Fe$ are given in Table 5. As can be seen from the table, the $R_0'$ value obtained in the calculation taking into account the contribution of distant negative resonances shows better agreement with the data in Ref. [1] compared with the calculation using the conventional approach.

The analysis of the total neutron cross-sections of $^{56,57}Fe$ performed in this paper showed that when allowance is made for the contributions of distant negative resonances in cross-section parametrization in the energy region below the first positive resonance, the values of the potential scattering radius $R_0'$ are in better agreement with the $R_0'$ value determined from analysis of data in a wide energy interval. Furthermore, in the case of $^{57}Fe$, use of the equidistant "palisade" of distant negative resonances somewhat improves the quality of experimental data parametrization. Thus, the results of the present work confirm our conclusion [6] that it is necessary to take distant negative resonances into account to achieve a correct parametrization of neutron cross-sections in the low energy region.

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TABLE 1. CHARACTERISTICS OF $^{54,56,57}Fe$ SAMPLES

| Sample | Thickness, g/cm$^2$ | Isotopic composition | | | |
|---|---|---|---|---|---|
| | | $^{54}Fe$ | $^{56}Fe$ | $^{57}Fe$ | $^{58}Fe$ |
| $^{54}Fe$ | 17.15 (17) | 99.93 | 0.07 | 0.005 | 0.005 |
| $^{56}Fe$ | 12.906 (10 | 0.3 | 99.5 | 0.2 | < 0.01 |
| $^{57}Fe$ | 10.111 (50) | 0.01 | 0.81 | 95.54 | 3.64 |

TABLE 2. THERMAL NEUTRON RADIATIVE CAPTURE CROSS-SECTIONS

| Nucleus | $\sigma^{th}_{\gamma}$, barn | | |
|---|---|---|---|
| | [1] | With allowance for distant negative resonances | Without allowance for distant negative resonances |
| $^{54}Fe$ | 2.25 $\pm$ 0.18 | 2.28 | 2.28 |
| $^{56}Fe$ | 2.59 $\pm$ 0.14 | 2.80 | 2.77 |
| $^{57}Fe$ | 2.48 $\pm$ 0.30 | 1.38 | 1.20 |

TABLE 3. RESONANCE PARAMETERS FOR $^{54}Fe$

| Calculation version | $\lambda$ | $E_\lambda$, keV | $\Gamma^0_{\lambda n}$, eV | $\Gamma_{\lambda\gamma}$, eV |
|---|---|---|---|---|
| With allowance for distant negative resonances | -1<br>1 | -38 $\pm$ 5<br>7.788* | 75 $\pm$ 9<br>13.77* | 1.8*<br>1.75 $\pm$ 0.14 |
| Without allowance for distant negative resonances | -1<br>1 | -51 $\pm$ 5<br>7.788* | 174 $\pm$ 10<br>13.77* | 1.8*<br>1.76 $\pm$ 0.14 |
| [1] | -1<br>1 | -25.1<br>7.67 $\pm$ 0.01 | 73.212<br>12.1 $\pm$ 0.2 | 1.17<br>1.8 $\pm$ 0.3 |

*/ - Values not varied during calculation; taken from BNAB-2 evaluated data file.

TABLE 4. RESONANCE PARAMETERS FOR $^{56}Fe$

| Calculation version | $E_{(-1)}$, keV | $\Gamma^0_{(-1)n}$, eV | $R'_0$ $\Phi$ Fermi |
|---|---|---|---|
| With allowance for distant negative resonances | -2.84 $\pm$ 0.17 | 5.77 $\pm$ 0.54 | 6.23 $\pm$ 0.16 |
| Without allowance for distant negative resonances | -2.94 $\pm$ 0.18 | 6.30 $\pm$ 0.61 | 7.13 $\pm$ 0.17 |
| [1] | -6.52 | 17.29 | 6.1 $\pm$ 0.3 |

TABLE 5. RESONANCE PARAMETERS FOR $^{57}Fe$

| Calculation version | $E_1$, keV | $\Gamma^0_{1n}$, eV | $R'_0$, Φ Fermi |
|---|---|---|---|
| With allowance for distant negative resonances | 4.107 ± 0.014 | 4.76 ± 0.16 | 5.84 ± 0.08 |
| Without allowance for distant negative resonances | 4.102 ± 0.015 | 4.80 ± 0.17 | 7.32 ± 0.09 |
| [1] | 3.955 ± 0.008 | 3.40 ± 0.26 | 5.9 ± 0.3 |

*FIGURE CAPTIONS*

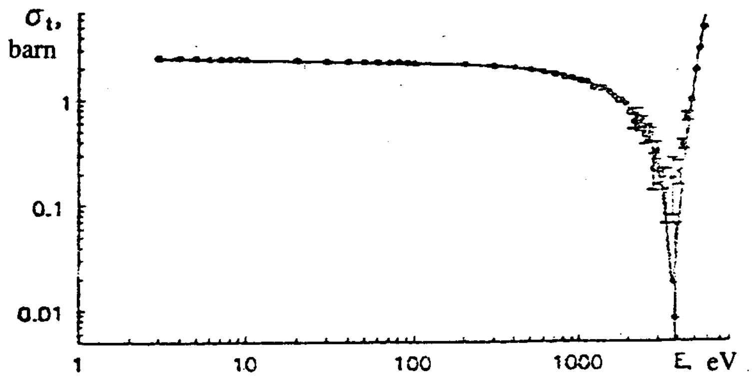


Fig. 1. *Total neutron cross-section for $^{54}Fe$. Points: experimental data; line: results of their approximation.*

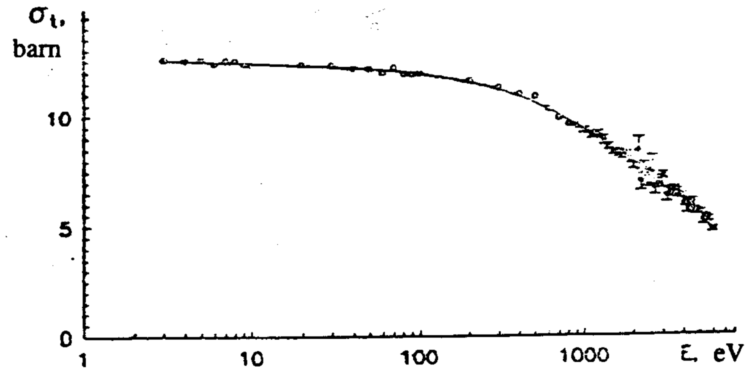


Fig. 2. *Total neutron cross-section for $^{56}Fe$. Points: experimental data; line: results of their approximation.*

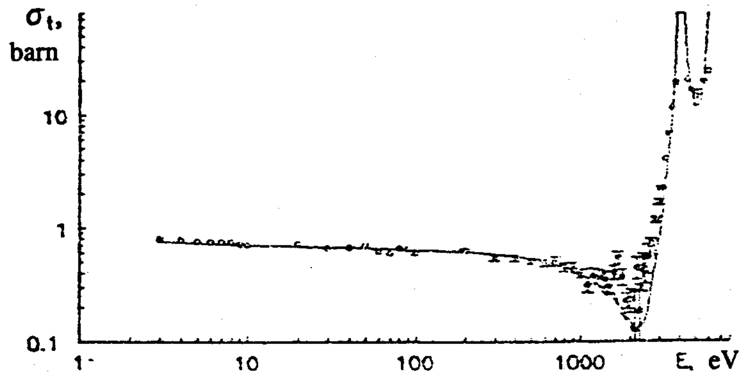


Fig. 3. *Total neutron cross-section for $^{57}Fe$. Points: experimental data; solid and dotted line: result of their approximation with and without allowance made for the contribution of distant negative resonances.*

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