International Atomic Energy Agency

INDC(CCP)-376
Distr.: L

INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

INVESTIGATION OF THE REACTIONS (n,p) AND (n,n'p) ON ^{27}Al, ^{28}Si, ^{50}Cr, ^{54}Fe, ^{56}Fe, ^{58}Ni AND Ni AT 14.1 MeV NEUTRON ENERGY

L.I. Klochkova, B.S. Kovrigin, V.N. Kuritsin
Technological Institute, St. Petersburg, Russia

(Translated from a Russian original published in Yadernye Konstanty 1/1992, p. 27-36)

Translated by the IAEA

August 1994

IAEA NUCLEAR DATA SECTION, WAGRAMERSTRASSE 5, A-1400 VIENNA

Reproduced by the IAEA in Austria
August 1994

INDC(CCP)-376
Distr.: L

94-10591 (C)
Translated from Russian

INVESTIGATION OF THE REACTIONS (n,p) AND (n,n'p) ON ^{27}Al, ^{28}Si, ^{50}Cr, ^{54}Fe, ^{56}Fe, ^{58}Ni, AND Ni AT 14.1 MeV NEUTRON ENERGY

L.I. Klochkova, B.S. Kovrigin, V.N. Kuritsin
Technological Institute, St. Petersburg

ABSTRACT

Investigation of the nuclear reactions (n,p) and (n,n'p) on 14 MeV neutrons, apart from its applied value, is also fundamental for correcting the systematics of cross-sections and other values, as well as for comparisons with models of nuclei and nuclear reactions. In this work the authors measured the energy and angular distributions of the products of the reactions (n,p) and (n,n'p) for elements contained in constructional materials. In addition, they determined the cross-sections of these reactions and compared them with the results of other works and recommended data. A charged-particle spectrometer was used in the experiment, the neutron source was a NG-200 generator, and the reaction employed was ^{3}H(d,n)^{4}He.

The investigation of the nuclear reactions (n,p) and (n,n'p) induced by 14 MeV neutrons is of fundamental importance for correcting the existing systematics of the cross-sections of these reactions and other nuclear parameters and also for comparisons with existing models of nuclei and nuclear reactions. In addition, these investigations have an applied character. For making a correct choice of constructional materials and assessing their radiation resistance it is necessary to know the cross-sections of the nuclear reactions (n,p) and (n,n'p) which are responsible for the accumulation of hydrogen in materials leading to destructive changes (swelling and embrittlement). Analysis of existing information shows that data on the cross-sections of the reaction (n,p) at $E_n \approx 14$ MeV are still incomplete and in some cases contradictory. Data on the reaction (n,n'p) exist only for a small number of nuclei and are not sufficiently reliable.

The majority of works concerned with the study of the reaction (n,p) are based on the activation method. However, with this method it is possible to determine only the integral cross-sections and it is impossible to obtain information about the mechanism of the reactions. Moreover, only part of the cross-section of the reaction (n,p) is determined, namely the cross-section of the reaction (n,pγ), whilst the contribution of the reaction (n,pn) remains unknown. Much more complete information is provided by methods of direct detection of the outcoming charged particles coupled with measurement of their energy and angle of emission. Such methods include the photoemulsion method, the shielded detector method, and the counter telescope method. In recent years new developments have emerged [1], the aim of which is to reduce the background and the threshold of recording and also to reduce the data recording time without greatly impairing the energy and angular resolution.

In the reference work [2] the authors present extensive information on the cross-sections of threshold reactions (including the reaction (n,p)) in a wide energy range, define more accurately the systematics of the cross-sections for $E_n \approx 14$ MeV and obtain a semi-empirical formula for the cross-sections of the reaction (n,p) at that energy, calculations on the basis of which agree with experimental data within a range of 25%. However, for practical purposes such accuracy is insufficient. For interpreting experimental data and for obtaining a preliminary estimate of the excitation functions of neutron reactions, one also employs theoretical calculations based on the statistical theory of nuclear reactions, the theory of pre-equilibrium emission and the theory of direct processes. The accuracy of calculations of the excitation functions for the reactions (n,p) and (n,n'p) in this case amounts to 30-40%.

Requirements for accuracy and completeness of nuclear data have now increased considerably, necessitating new measurements together with further development of experimental methods and ways of treating data.

In the present work, the authors investigated the nuclear reactions (n,p) and (n,n'p) on nuclei of ^{27}Al, ^{28}Si, ^{50}Cr, ^{54}Fe, ^{56}Fe, ^{58}Ni, and Ni in its natural isotopic composition for energy E_n = 14.1 MeV. The choice of targets was determined by their use in constructional materials (especially in stainless steel).

1. Experimental method

Measurements of the energy spectra and angular distributions of the reactions (n,p) and (n,n'p) at energy 14.1 MeV were performed on a charged-particle spectrometer incorporating a counter telescope and electronic equipment. The telescope consists of two gas proportional counters and a silicon semiconductor detector. One of the gas counters measures the particle energy loss ΔE over a fixed section of the path, while the detector measures the residual energy E. The charged particles are identified by means of two-dimensional (ΔE,E) analysis.

The distance from the neutron source to the target is 12 cm, and from the target to the detector 24 cm. The investigated targets have a diameter of 30 mm and a surface density of (10-15) mg/cm^2. The diameter of the silicon detector is 20 mm and the depth of the sensitive layer 1.2-1.4 mm. To measure the angular distributions of the charged particles, the telescope can be rotated around its vertical axis, whereby the angle θ between the direction of the neutron beam and the telescope axis varies from 0° to 140°. With the telescope set at an angle θ = 0°, the mean angle of particle recording is equal to 6°. Starting from θ = 15°, the recording angle practically coincides with the angle of setting of the telescope. The counter telescope is filled with a mixture of argon (90%) and CO_2 (10%)

at a pressure of 80 mmHg. The energy calibration of the spectrometer is performed with respect to the spectrum of the products of the interaction of 14.1 MeV neutrons with silicon nuclei of the semiconductor detector. For normalizing the cross-sections of the investigated reactions and identifying the location of the protons, one measures the two-dimensional distribution of recoil protons from pr scattering on hydrogen nuclei of a polythene target 7.45 mg/cm^2 thick. Neutrons are produced on a NG-200 generator from the reaction ^{3}H(d,n)^{4}He. Measurements are performed at neutron energy 14.1 MeV with a 4π flux of (0.5-1.0)$\cdot 10^9$ s^{-1}. The neutron flux is determined and monitored by a detector of accompanying alpha particles, a long counter and a silicon semiconductor detector.

2. Results of the experiment

In this work we measured the spectra of protons formed in the reactions (n,p) and (n,n'p) from the interaction of 14.1 MeV neutrons with targets consisting of the isotopes ^{27}Al, ^{28}Si,^{50}Cr, ^{54}Fe, ^{56}Fe, ^{58}Ni and natural Ni. The measurements were performed at the following telescope setting angles with respect to the direction of the neutron beam: ^{27}Al from 0 to 135° in steps of 15°; ^{28}Si at 80°; ^{50}Cr from 20 to 120° in steps of 20°; ^{54}Fe from 0 to 120° in steps of 20°; ^{56}Fe from 20 to 100° in steps of 20°; and ^{58}Ni and Ni at 80°. The two-dimensional (ΔE,E) distributions were measured for these targets both with a target in the telescope (effect plus background) and without a target in the telescope (just background). The experimental data were processed according to set programmes: the two-dimensional distributions were converted to unidimensional spectra within the area of location of protons, the background events were calculated from the spectra, the energy calibration of the scale of the spectrum channels was carried out, the spectrum was corrected for proton energy losses in the target and the telescope gas and for the background from scattered neutrons, and the energy and cross-sections were converted from the laboratory system of co-ordinates to the centre-of-mass system.

According to current theory, the two-particle nuclear reaction (n,p) under the effect of moderate-energy neutrons can occur via three basic processes: direct interaction - DI, pre-equilibrium emission (precompound emission - PCE) and evaporation of a proton from the compound nucleus (compound emission - CE). The emission of a proton in the reaction (n,n'p) is an almost entirely evaporative process and small contributions from the PCE and DI processes may be neglected.

The energy spectra for the reactions (n,p) and (n,n'p) obtained as a result of primary treatment are sum spectra of the protons of these reactions for one angle of emission of a proton or spectra integrated with respect to the angle within the limits of a specific angular range. In order to extract physical information, it is necessary to divide the measured spectrum into the spectra of these reactions. This task is achieved by fitting the theoretical spectrum to the experimental one using the non-linear least-squares method. The former is constructed on the basis of existing models of the nuclear structure and nuclear reactions.

The methodology for analysing the experimental spectrum of the reactions (n,p) and (n,n'p) is set out in Ref. [3], and a short description is given here. The evaporation spectrum (n,p) is approximated in terms of the Weisskopf-Ewing theory [4]. For the level density with excitation energy $U < U_c$ where U_c is the critical energy of transition of the residual nucleus from the superfluid to the normal state, the approximation of constant temperature $\rho(U) \sim \exp(U/T)$ is used, where T is the temperature of the residual nucleus after emission of the proton. When $U > U_c$, the weighted mean of the level density over the finite states of the residual nucleus for the levels populated in the nuclear reaction was used [5]:

$$\rho\,(U) = \overline{\rho\,(U,J)} \approx \exp\left(2\sqrt{a(U-\delta)}\right) / \left(U-\delta\right)^{n} .$$

where δ is the usual correction for pairing energy. The value 1.34 was taken for the parameter n [6]. Two representations of $\rho(U)$ were normalized for U = Uc. The parameter a was recalculated in each iteration according to the formula $a = (U_c - \delta)(1/T + n/(U_c - \delta)^2$.

Each spectrum for a given value of the angle θ, where θ is the angle in the centre-of-mass system between the directions of the incident and the outcoming particles, was divided into three partial spectra: the proton spectrum of the reaction (n,n'p), the evaporation and the non-equilibrium spectra of the reaction (n,p). The proton spectrum of the reaction (n,p) was integrated with respect to energy and used to obtain the experimental angular distribution of the reaction (n,p). The angular distribution was analysed with the aid of the sum of the two functions $\sigma_{n,p}(\theta) = \sigma_1(\theta) + \sigma_2(\theta)$, where $\sigma_1(\theta)$ and $\sigma_2(\theta)$ are the angular distributions respectively of the statistical processes (evaporation and precompound emission) and a non-statistical (direct) process. The function $\sigma_1(\theta)$ is anisotropic but symmetrical with respect to $\theta = 90°$, and was approximated as $\sigma_1(\theta) = \sigma_1(90°)(1 + \alpha\cos^2\theta)$ where α is the anisotropy parameter. The function $\sigma_2(\theta)$, which has an asymmetric and an isotropic component, takes the form $\sigma_2(\theta) = \sigma_2(90°)(1 + \gamma\cos\theta)$ where γ is the asymmetry parameter, which in accordance with Ref. [7] was taken as equal to 0.5.

Figures 1-7 show the experimental energy spectra of protons in the centre-of-mass system for the target nuclei ^{27}Al, ^{28}Si, ^{50}Cr, ^{54}Fe, ^{56}Fe, ^{58}Ni, and Ni as well as the proton spectra obtained during separation of the equilibrium and non-equilibrium processes of the reaction (n,p) and the proton spectrum of the reaction (n,n'p). Fitting provided the contribution of the non-equilibrium processes to the spectrum of the reaction (n,p) for ^{27}Al, which is equal to 6.0%. In the case of ^{50}Cr for the spectrum in the range 50-110° the contribution of the non-equilibrium processes amounts to 16.4%, while for the spectrum in the range 70-110°, symmetric with respect to $\theta = 90°$, it is equal to 14.7%. In the case of

^{28}Si, ^{54}Fe, and ^{58}Ni the contribution of non-equilibrium processes to the spectra of the reaction (n,p) lies within the error limits and does not exceed 5%. Therefore, for these nuclei, analysis of the experimental spectra was performed without regard to the non-equilibrium processes.

For ^{27}Al, ^{50}Cr and ^{54}Fe the proton spectrum of the reaction (n,n'p) commences from the threshold determined by the dependence of $\sigma_c(\epsilon)$ on the energy. For ^{28}Si the maximum proton energy from the reaction (n,n'p) is equal to $\sim$ 2 MeV, which coincides with the proton recording threshold in this experiment. For ^{56}Fe the channel of the reaction (n,n'p) is closed up to energy ϵ = 2.65 MeV owing to the competition of the reaction (n,2n), and the maximum energy of protons from this reaction cannot exceed $\epsilon_{max} = \epsilon_0 - S_p = 3.66$ MeV. Thus, the emission of protons from the reaction (n,n'p) on ^{56}Fe is possible only in an energy range with a width of around 1 MeV.

Figure 8 shows the experimental angular distributions of the reaction (n,p) and the calculated angular distributions obtained on fitting the approximating expression. From the angular distribution for ^{27}Al it follows that the contribution of the direct process is close to 50%. The deviation of this estimate from the result obtained in the analysis of the proton spectrum of the reaction (n,p) may be explained by the fact that this spectrum has a structure of lines and groups of lines, and it would be difficult to expect a correct result from the application of a statistical consideration to this. Therefore, preference was accorded to an estimate of the fraction of the direct interaction obtained from the angular distribution. For ^{50}Cr and ^{54}Fe the absence of data for θ > 120° meant that the formal result for the asymmetric component obtained by fitting could not be considered conclusive enough. Therefore, in the case of ^{50}Cr we fitted the expression with the same contribution of the direct process which was found in the analysis of the spectrum integrated with respect to the angle in the range $\theta = 7\text{-}110°$. For ^{54}Fe the angular distribution is described satisfactorily by the expression $1 + \cos^2\theta$ and does not point to the presence of a significant asymmetric component. In the reaction (n,p) on ^{56}Fe the experimental values of $\sigma(\theta)$ did not reveal any structure of the angular distribution. Since the data did not contradict the basic assumption as to the isotropism of the angular distribution, it was adopted and used henceforth in calculating the cross-section of the reaction (n,p).

The cross-section of the reaction (n,p) for ^{27}Al, ^{50}Cr and ^{54}Fe was found by integrating the fitted angular distribution over the whole range of the angle θ from 0° to 180°: $\sigma_{n,p} = 2\pi \int_0^\pi \sigma_{n,p}(\theta) \sin\theta d\theta$. In the case of ^{56}Fe the cross-section of the reaction (n,p) was found as $\sigma_{n,p} = 4\pi\overline{\sigma_{n,p}(\theta)}$, whereby averaging of $\sigma_{n,p}(\theta)$ was performed on the basis of the most reliable values for 40, 60 and 80°. For ^{28}Si, ^{58}Ni and Ni the cross-section of the reaction (n,p) was determined as $\sigma_{n,p} 4\pi\sigma_{n,p}$ (80°). The distribution of protons of the reaction (n,n'p) was considered isotropic in all cases. The cross-sections and the contributions of the equilibrium and the direct processes are shown in Table 1. The errors indicated correspond to a probability level of $P = 0.68$.

Table 2 shows the values of the nuclear temperature T, the density level parameter and the excited residual nucleus obtained from the proton spectra of the reaction (n,p). For nickel of natural isotopic composition, the values of T and *a* have a formal character.

3. Discussion of results

About 40 works are known in which reactions with emission of protons were investigated for ^{27}Al at neutron energy 14-15 MeV. More than 20 of these were performed using the activation radiochemical method. This method enables one to determine only a single value - the cross-section of the reaction (n,pγ) - which is the principal branch of the reaction (n,p). The averaged cross-section from these works is $\sigma_{n,p\gamma} = 74.4 \pm 3.4$ mb.

More information is provided by methods of direct measurement of the energy and angle of proton emission. The main ones are the photoemulsion and the counter telescope method. The averaged value of the cross-section measured by these methods is equal to $\sigma_{n,p}$= 86.6 $\pm$ 9.0 mb. The cross-section of the reaction (n,np) on ^{27}Al was determined in only five works. If one disregards the result of 17 mb which differs sharply from the others, the averaged value is equal to 103 $\pm$ 21 mb. The relationship $\sigma_{n,np}/\sigma_{n,p}$ = 103/86.6 = 1.19. The maximum ratios of these cross-sections, namely 1.35 and 2.1, were obtained in Refs [8, 9]. In Ref. [10] a theoretical calculation was carried out on the basis of statistical theory and values of 72 and 79 mb were obtained for $\sigma_{n,p}$ and $\sigma_{n,np}$. The absolute values of the cross-sections in such calculations are insufficiently reliable, but their ratio merits greater confidence. In this work, the ratio of the cross-sections amounts to 1.1, which agrees with previous experimental and theoretical results. These data indicate that in radiation damage of aluminium the contribution of the reaction (n,n'p) can exceed the contribution of the reaction (n,p). In the investigation in Ref. [11], which was performed on a spectrometer with a counter telescope and quadrupole magnetic focusing, the sum cross-section of the reactions (n,p) and (n,n'p) for energy E_n = 15 MeV was determined from the spectrum integrated over the angle. The result $\sigma_{n,p} + \sigma_{n,n'p}$ = 399 $\pm$ 60 mb considerably exceeds both the sum cross-section of 189 $\pm$ 23 mb, averaged over the previous works and the sum cross-section of 207 $\pm$ 32 mb from the present work. The cause of such divergence could be the nature of the measuring methods employed and the form of treatment of the data in Ref. [11].

The cross-section of the reaction (n,p) on ^{28}Si for neutron energy 14-15 MeV was determined in 13 works. Ten of these were performed by the activation method. The averaged cross-section for these works is $\sigma_{n,p}$ = 230 $\pm$ 21 mb. In Ref. [10] performed by the photoemulsion method, the result obtained was $\sigma_{n,p} = 243 \pm 22$ mb. This is the only work in which an attempt was made to determine the cross-section of the reaction (n,n'p) on ^{28}Si, and the result obtained was $\sigma_{n,n'p} = 27 \pm 22$ mb. The fact is that the maximum energy of a proton from the reaction ^{28}Si(n,n'p)^{27}Al is equal to ~ 2 MeV which is on a level with or below the proton recording threshold in the majority of experiments. In Ref. [12] two silicon semiconductor detectors connected in coincidence were employed, so that each was simultaneously both target and detector. The energy spectra were measured starting with proton energy ~ 6 MeV in the range of angles 0-180°C. With reduction of energy in this method of measurement the proportion of protons emitted from the target decreases monotonously. This is equivalent to a reduction in proton recording efficiency and leads to distortion of the spectrum obtained. However, no correction was made in the work for this distortion and the cross-section was not determined. The angular distributions for successive energy ranges are given in the work. The counter-telescope method was employed in Ref. [13]. Measurements were performed in the range of angles 0-150° in steps of 30°, which made it possible to obtain an angular distribution integrated with respect to energy. The cross-section of the reaction (n,p) was determined as equal to 160 ± 16 mb. The contribution of the direct process was estimated as 10%. In this work the counter-telescope method was employed, and (E,ΔE) analysis was used for identifying the charged particles and reducing the spectrometer background. The proton recording threshold was reduced to 2 MeV. The proton energy spectrum was measured at $\theta = 80°$. The cross-section of the reaction (n,p) for ^{28}Si was obtained as 289 ± 13 mb. This value of the cross-section agrees with the results of Refs [10, 14 and 15], which were 243 ± 22, 265.0 ± 7.5, and 269.4 ± 9.8 mb respectively, but is greater than the cross-section measured in Ref. [10], namely

160 ± 16 mb, and the average cross-section of the reaction (n,pγ) which was determined by the activation method as 228 ± 20 mb.

For investigating reactions with proton emission on ^{50}Cr, the activation method is inapplicable, since the residual nucleus of ^{50}V after the reaction (n,p) is stable. Two experimental works are known for neutrons with energy around 14 MeV. In Ref. [10] (based on the photoemulsion method) the proton energy spectrum of these reactions was measured for an angle of emission of 120° at a neutron energy of 14 MeV, but the spectrum is not given in this publication. The cross-sections of the reactions (n,p) and (n,n'p) are determined as 265 ± 21 mb and 153 ± 21 mb respectively. The relative contributions of the reactions (n,p) and (n,n'p) to the sum cross-section obtained in the present work (65% and 35%) agree both with the experimental data of Ref. [10] (64% and 36%) and with the calculations based on statistical theory performed in this work (61% and 39%). In Ref. [16] the authors measure the energy spectra of protons from the reactions (n,p), (n,n'p) for six angles of emission from 22° to 135° with E_n = 14.8 MeV. The spectrum integrated with respect to the angle is given. The sum cross-section of the reactions (n,p) and (n,n'p) is determined as 830 ± 100 mb. The sum cross-section obtained in the present work, 593 ± 53 mb, occupies an intermediate position between the results of Ref. [10], namely 418 ± 27 mb, and Ref. [16]. In Ref. [2] the recommended values given are $\sigma_{n,p} = 300 \pm 50$ mb and $\sigma_{n,n'p} = 150 \pm 30$ mb. In Ref. [17] a value of $\sigma_{n,p} = 235 \pm 10$ mb is recommended. The values obtained in the present work and the result of Ref. [16] provide bases for correcting the recommended cross-sections.

Reactions with proton emission under the effect of neutrons with energy around 14 MeV on ^{54}Fe were investigated in 17 experimental works. In seven of these the activation method was employed. The averaged cross-section of the reaction (n,pγ) for these works is $\sigma_{n,p\gamma}$ = 308 ± 29 mb. In the other works, the proton energy spectra were measured for one or several values of the angle of emission, but the cross-section of the reaction (n,p) was determined in only four of them [10, 18-20], using the photoemulsion method. The averaged value of $\sigma_{n,p}$ = 389 ± 18 mb. The difference between the two averaged values gives an estimate of the cross-section of the reaction (n,pn) $\sigma_{n,pn}$ = 81 ± 34 mb. Comparison of the result obtained in the present work, namely $\sigma_{n,p}$ = 417 ± 34 mb, with the averaged value of 308 ± 29 mb gives $\sigma_{n,pn}$ = 109 ± 45 mb. For further refinement of the cross-section of the reaction (n,pn) new measurements are required. With respect to the cross-sections of the reaction (n,p) 365 ± 30 and 287 ± 13 mb recommended in Refs [2 and 7] it can be said that they are most likely underestimated, since in the averaging process the greatest weight was accorded to data from investigations carried out by the activation method. The cross-section of the reaction (n,n'p) was determined in the same four works. The averaged cross-section $\sigma_{n,n'p}$ = 214 ± 5 mb. The result of the present work $\sigma_{n,n'p}$ = 240 ± 30 mb is in satisfactory agreement with the averaged value, but the cross-section $\sigma_{n,n'p}$ = 110 mb recommended in Ref. [2] seems too low. In Ref. [16], the sum cross-section of both reactions is obtained as equal to 900 ± 110 mb. This result notably exceeds both the sum cross-section of the present work of 657 ± 45 mb and the sum of the averaged values for the four works mentioned of 603 ± 19 mb.

Thirty-eight experimental works have been published in which nuclear reactions with emission of protons under the effect of neutrons with energy around 14 MeV on ^{56}Fe, the basic isotope of iron, were investigated. Of these works, 26 were carried out by the activation method. The average cross-section from these works $\sigma_{n,p\gamma}$ = 112.0 ± 1.6 mb. The total cross-section of the reaction (n,p) was determined in four works. Two of these [10, 18] were performed by the photoemulsion method, one [13] by the telescope method, and the other [21] by the shielded detector method. The averaged value for these works is $\sigma_{n,p} = 92 \pm 14$ mb. The cross-section obtained in the present work is $\sigma_{n,p} = 139 \pm 25$ mb. In Ref. [17] a recommended value of $\sigma_{n,p} = 98.3 \pm 2.6$ mb is given. The cross-section of the reaction (n,n'p) for ^{56}Fe was determined in two works [10, 18]. In Ref. [18] the presence of protons from the reaction (n,n'p) in the spectrum for ^{56}Fe was not detected. In Ref. [10] the value $\sigma_{n,n'p} = 35 \pm 7$ mb was obtained but the experimental spectrum is not given in the work. The present work provides a quantitative estimate of the cross-section of the reaction (n,n'p) and confirms the conclusion that the cross-section of the reaction (n,n'p) on ^{56}Fe is small. In Ref. [16] the energy spectrum of proton emission for ^{56}Fe at $E_n = 14.8$ MeV integrated over the angle was obtained. The authors of Ref. [16] supply only the sum cross-section of proton emission equal to 190 ± 22 mb which exceeds the sum cross-section of the present work and the recommended values.

The reaction (n,p) on ^{58}Ni was investigated in 14 works, of which seven were performed by the activation method. The cross-sections obtained in these works lie within the range 125-560 mb. In Ref. [16] the proton energy spectrum integrated with respect to the angle is obtained for ^{58}Ni at $E_n = 14.8$ MeV. Only the sum cross-section of proton emission, equal to 1000 ± 120 mb, is supplied. If the experimental spectrum is divided into spectra of the reactions (n,p) and (n,n'p), a value of 585 ± 80 mb is obtained for the cross-section of the reaction (n,p). In the present work a value of $\sigma_{n,p} = 606 \pm 32$ mb was obtained. The value $\sigma_{n,p} = 344 \pm 17$ mb recommended in Ref. [17] seems too low. The cross-section of the reaction (n,n'p) on ^{58}Ni was determined in eight works. The values obtained lie within the range 150 ± 415 mb. In the present work the value obtained for $\sigma_{n.n'p} = 357 \pm 22$ mb. Here no contribution to the cross-section of the reaction (n,p) from non-equilibrium processes exceeding the statistical error limits was detected. This is not in accordance with the results of Ref. [22] where the authors calculated the cross-section of direct excitation of low-lying states in the reaction $^{58}Ni(n,p)^{58}Co$ for neutrons with energy 0.1-6.5 and 18.5 MeV, and showed that the contribution of the direct mechanism in the reaction is considerable and can determine the behaviour of the hard part of the proton emission spectrum.

The nuclear temperatures of the residual nuclei from proton spectra of the reaction (n,p) at neutron energies of around 14 MeV were determined in almost all works in which these spectra were measured. A specific trend is apparent in the results. For each of these nuclei the mean value of the nuclear temperature for works performed by the photoemulsion method is considerably less than the mean from works with electronic proton recording. For example, for ^{27}Mg, ^{28}Al, ^{54}Mn, ^{56}Mn and ^{58}Co, the results of the former group of works give mean values respectively of 1.25; 1.5; 1.17; 1.15; and 1.2 MeV, and those of the latter group 1.81; 1.81; 1.52; 1.42; and 1.61 MeV. The values of the nuclear temperature T obtained in the present work for these nuclei agree better with results of the latter group. The nuclear temperature of the residual nucleus of ^{50}V was determined only in one work [10], using the photoemulsion method, and a value T = 1.1 MeV was obtained. In the present work $T = 1.42 \pm 0.06$ MeV. The causes of this trend could be specific distortions of the proton spectrum in the photoemulsion method, for example, owing to the dependence of the ionization effect of recording on proton energy and the absence of a corresponding correction.

On comparing the values for the level density parameter *a* obtained in the present work with the existing systematics of this parameter it is noticeable that the values of the parameter from the systematics in Ref. [23] for ^{50}B, ^{54}Mn and ^{56}Mn of 7.00; 7.56; and 7.84 MeV^{-1} considerably exceed the experimental values calculated according to the Fermigas model with the usual shift. This result can be taken as an argument in favour of determining the parameter *a* of the system of levels of a nucleus for single-particle excitations from the energy spectra without allowance for the collective degrees of freedom. In Ref. [24] this conclusion is drawn in relation to the level density of deformed nuclei with $A \geq 150$. The results of the present work indicate that this assertion evidently applies also to certain intermediate-mass nuclei with $A \sim 50\text{-}60$. From the value of the parameter *a* for a ^{27}Mg nucleus it is difficult to draw any conclusions owing to the fact that the application of a statistical consideration is problematic for such a light nucleus. For ^{28}Al the value $a = 3.5 \pm 1.0\ MeV^{-1}$ obtained in this work agrees with the value $3.9\ MeV^{-1}$ from the systematics given in Ref. [23]. For ^{58}Co the value obtained for *a* of $5.14 \pm 0.55\ MeV^{-1}$ agrees better with the value $5.4\ MeV^{-1}$ from the systematics in Ref. [24], in which the contributions of the collective states are excluded from the level density, and does not agree with the systematics in Ref. [23] which give a value $a = 8.12\ MeV^{-1}$.

Conclusions

1. The cross-sections of the reaction (n,p) and (n,n'p) were determined for the nuclei investigated and compared with the results of other works and the recommended cross-sections.

2. Analysis of the energy spectra and the angular distributions revealed certain features associated with the competition of the statistical processes and the direct process in the nuclear reaction (n,p):

   (a) The contribution of the direct interaction in the reaction on ^{27}Al is close to 50%;

   (b) In the reaction on ^{50}Cr the contribution of the direct interaction is estimated as 15%;

(c) In the reaction on ^{28}Si, ^{54}Fe and ^{58}Ni no contribution of the direct process exceeding the statistical error limits is observed.

3. The values of the nuclear temperature were determined from the regions of the spectra with $V < V_c$ and compared with existing data.

4. The values of the parameter *a* of the level density for the normal state of excited residual nuclei were calculated from the values obtained for T and compared with the basic systematics of this parameter.

REFERENCES

[1] VONACH, H., Neutron induced react., Proc. 2nd Int. Symp. Phys. and Appl. 6 (1980) 59.

[2] BYCHKOV, V.M., MANOKHIN, V.N., PASHENKO, A.B., PLYASKIN, V.I., Cross-sections of threshold reactions induced by neutrons, Moscow, Ehnergoizdat (1982).

[3] KLOCHKOVA, L.I., KOVRIGIN, B.S., Neutron physics (Proc. 6th All-Union Conf. on Neutron Physics) 4 (1984) 381.

[4] WEISSKOPF, V.P., EWING, D.H. Phys. Rev. 57 (1940) 472.

[5] THOMAS, T.D., Nucl. Phys. 53 (1964) 558.
IGNATYUK, A.V., SHORIN, V.S., Yadernaya fizika 12 (1970) 1203.

[6] IGNATYUK, A.V., SOKOLOV, Yu.V., Yadernaya fizika 19 (1974) 1229.
SIMAKOV, S.P., et al., Yadernaya fizika 38 No. 1 (1983) 3.

[7] BIRYUKOV, N.S., et al., Yadernaya fizika 25 No. 4 (1977) 767.
IGNATYUK, A.V., et al., Preprint FEhI-682 (1976).

[8] CLOVER, R.N., WEIGOLD, E., Nucl. Phys. 24 (1961) 630.

[9] ALVAR, K.R., Nucl. Phys. 195 (1972) 289.

[10] ALLAN, D., Nucl. Phys. 24 (1961) 274.

[11] GRIMES, S.M., HAIGHT, R.C., ANDERSON, T.D., Nucl. Sci. and Eng. 62 (1977) 187.

[12] MORGENSTERN, H., et al., Nucl. Phys. 83 (1966) 369.

[13] HASSLER, F., Phys. Rev. 125 (1962) 1011.

[14] ROBERTSON, J., et al., Nucl. Energy. 27 (1973) 139

[15] SHEBOLEV, V.T., RAMENDUK, Z.A., MOISEEV, N.N., (Proc. 3rd All-Union Conf. on Metrology of neutron radiation in reactors and accelerators), Moscow, TsNIIatominform 2 (1983) 196.

[16] GRIMES, S.M., et al., Phys. Rev. C. 19 (1979) 2127.

[17] BADIKOV, S.A., PASHCHENKO, A.B., Comparative analysis of (n,p) reaction cross-section systematics for 14-15 MeV neutrons: Report FEI-2055 (1989) 1991.

[18] MARCH, P.V., MORTON, W.T., Phil. Mag. 3 (1958) 143.

[19] ALLAN, D., Nucl. Phys. 10 (1959) 348.

[20] ALLAN, D., Proc. Phys. Soc. A70 (1957) 195.

[21] STOREY, R., JACK, W., WARD, A., Proc. Phys. Soc. 75 (1960) 526.

[22] BORZOV, I.N., PRONYAEV, V.G., TRYKOV., E.L., Neutron physics (Proc. 1. Internat. Conf. on Neutron Physics) 2 (1988) 144.

[23] BADA, H., Nucl. Phys. A159 No. 2 (1970) 625.

[24] IGNATYUK, A.V., ISTEKOV, K.K., SMIRENKIN, G.N., Yadernaya fizika, 29 (1979) 875.

Table 1

Target nucleus	$\sigma_{n,p}$, mb	Contribution of evaporation process, %	Contribution of direct process, %	$\sigma_{n,n'p}$, mb	$\sigma_{n,p} + \sigma_{n,n'p}$, mb
^{27}Al	99±11	54	46	108±30	207±32
^{28}Si	289±13	~100			289±13
^{50}Cr	381±33	85	15	212±42	593±53
^{54}Fe	417±34	~100		240±30	657±43
^{56}Fe	139±25	~100		4,6±1,2	144±25
^{58}Ni	606±32	~100		358±22	964±39
Ni	432±32	~100		242±35	674±47

Table 2

Target nucleus	Residual nucleus	T,MeV	a, MeV^{-1}
^{27}Al	^{27}Mg	1,68±0,07	3,98±0.33
^{28}Si	^{28}Al	2,1±0,3	2,7±1,0
^{50}Cr	^{50}V	1,42±0,06	5,69±0.45
^{54}Fe	^{54}Mn	1,53±0,01	5,11±0,24
^{56}Fe	^{56}Mn	1,41±0,02	5,74±0.24
^{58}Ni	^{58}Co	1,5±0,1	5,15±0,55
Ni		1,2±0,2	7,2±2,0

FIGURES

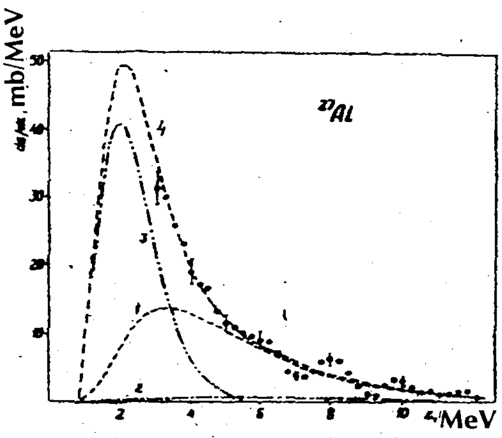

Fig. 1. Proton spectrum of the reactions (n,p) and (n,n'p) on ^{27}Al, integrated over the angle θ in the range 7.5-127.5. The points represent the experimental data of the present work. The calculated spectra are: 1 - the equilibrium spectrum of the reaction (n,p); 2 - the non-equilibrium spectrum of the reaction (n,p); 3 - the proton spectrum of the reaction (n,n'p); 4 - the sum spectrum.

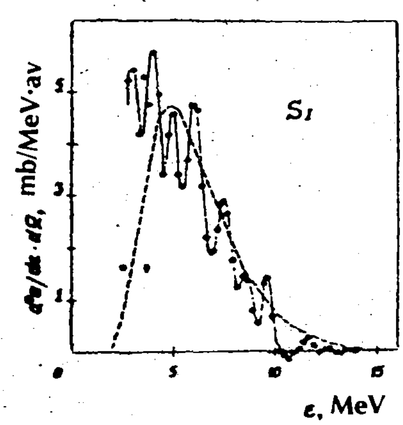

Fig. 2. Proton spectrum of the reaction (n,p) on ^{28}Si, measured at angle θ = 80°. The points represent the experimental data of the present work. The dashed curve is the calculated spectrum of the reaction (n,p).

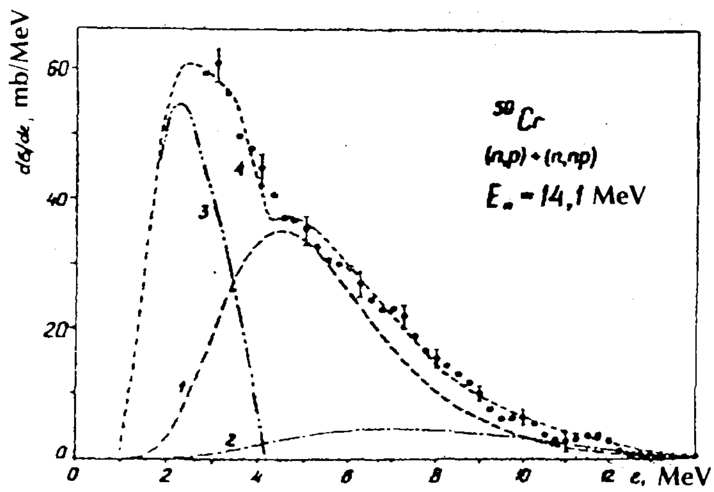

Fig. 3. Proton spectrum of the reactions (n,p) and (n,n'p) on ^{50}Cr, integrated over the angle θ in the range 50-110°. The points represent the experimental data of the present work. The calculated spectra are: 1 - equilibrium spectrum of the reaction (n,p); 2 - non-equilibrium spectrum of the reaction (n,p); 3 - proton spectrum of the reaction (n,np); 4 - sum spectrum.

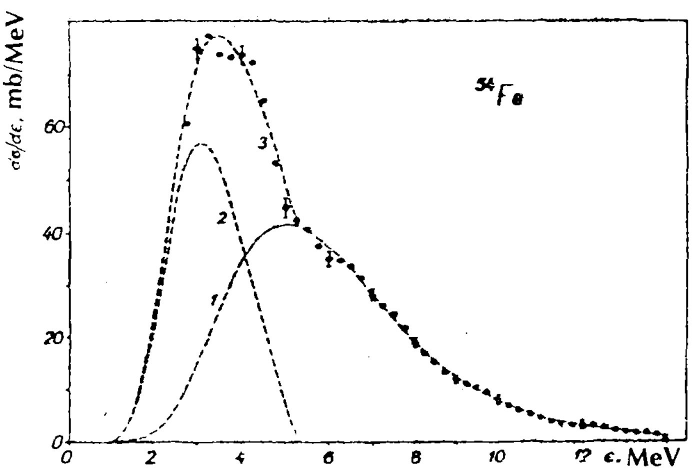

Fig. 4. Proton spectrum of the reactions (n,p) and (n,n'p) on ^{54}Fe, integrated over the angle θ in the range 50-110°. The points represent the experimental data of the present work. The calculated spectra are: 1 - spectrum of the reaction (n,p); 2 - proton spectrum of the reaction (n,n'p); 3 - sum spectrum.

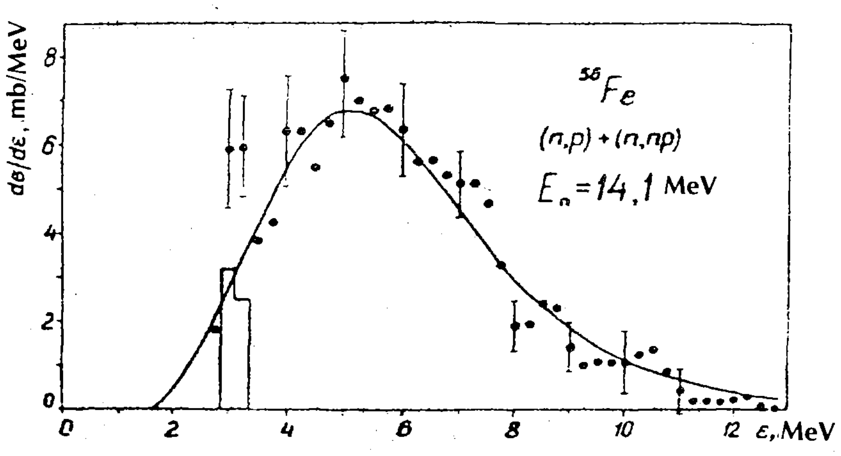

Fig. 5. Proton spectrum of the reactions (n,p) and (n,n'p) on ^{56}Fe, integrated over the angle θ in the range 30-70°. The points represent the experimental data of the present work. The smooth curve is the calculated spectrum of the reaction (n,p). The histogram is the proton spectrum of the reaction (n,n'p).

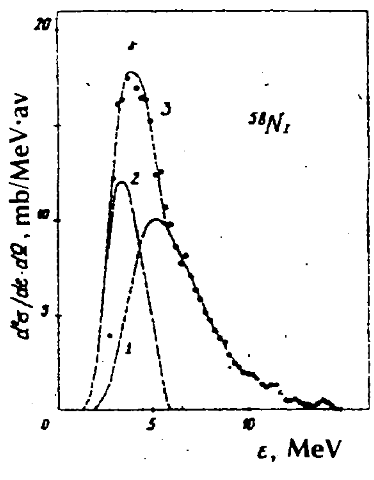

Fig. 6. Proton spectrum of the reactions (n,p) and (n,n'p) on ^{58}Ni measured for angle θ = 80°. The points represent the experimental data of the present work. The calculated spectra are: 1 - equilibrium spectrum of the reaction (n,p); 2 - proton spectrum of the reaction (n,n'p); 3 - sum spectrum.

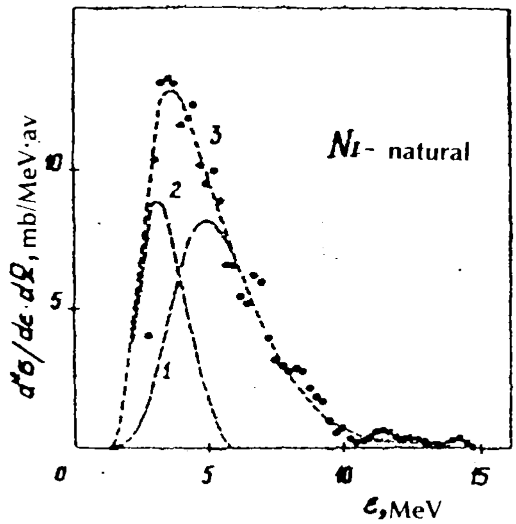

Fig. 7. Proton spectrum of the reactions (n,p) and (n,n'p) on Ni, measured at angle $\theta = 80°$. The points represent the experimental data of the present work. The calculated spectra are: 1 - equilibrium spectrum of the reaction (n,p); 2 - proton spectrum of the reaction (n,n'p); 3 - sum spectrum.

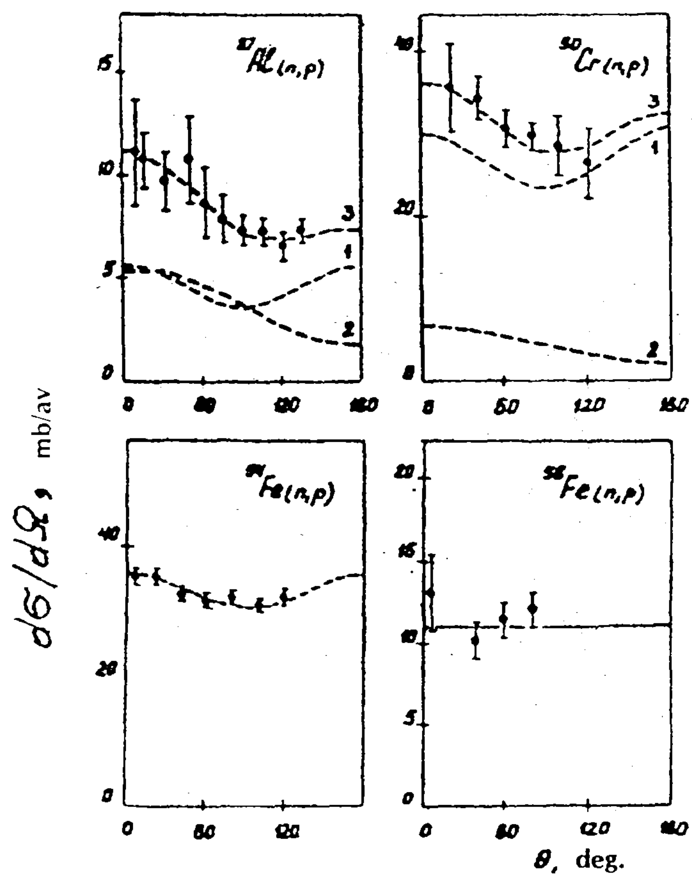

Fig. 8. Angular distributions of protons of the reaction (n,p) on ^{27}Al, ^{50}Cr, ^{54}Fe and ^{56}Fe. The points represent experimental data of the present work. The calculated curves are: 1 - angular distribution of the statistical processes; 2 - angular distribution of the direct process; 3 - sum curve.

94-02850