BULLETIN
OF THE
INFORMATION CENTRE FOR NUCLEAR DATA
(First Issue)
$(I C D-1)$

Editorial Board:
A. ․ I. Leipunsky (Editor-in-Chief),
O. D. Käzachkovsky, A。V. Mialyshev
M. N. Nikolaev (Responsible Editor), Sh. S. Nikolaishvili, Yu. Ya, Stavissky, G. A. Tabulevich, I. No Usachev, S. G. Tsypin

FOREWORD
This Bulletin is the Plrst of an intended series of rogular issues of collected information from tho Nucloar Data Contre set up by the State Committe on the Utilization of Atomic Enorgy to ensure the sollation, systematization an exchange of information on nuclear physical constants.

The contents and layout of the Information Centro's bulletins are determi by the need to prosent in conveniont form, in as short a time as possible, the existing information on nuclear data.

The Bulletin will therefore include only information which has been collected and systematimed by the groups of the Information Centre at the moment of publication. For this reason the issueg of the Bulletin, including this volume, lay no claim to providing a complete and ordered compilation of al the existing information on nuolear data. It is however assumed that the gap. in individual issues will be made good in subsequent numbers.

The present Bulletin includes data on the paraneters of the elementary interactions of neutrons with a substance (in the energy range of interest for reactor construction, i.e. E not exceeding approximately 15 MeV ), and the macroscopic constants, empirical formulae and integral parameters (and characteristics of such parameters) used in calculations for reactors and reactor shieldings, to the extent that such information is not contained in previous publications by the Publishing House for Atomic Literature (Atomizdat Most of the data given were obtained in 1963-64, or became available during this period. The material given varies widely in its degree of completeness. For example, capture and elastic and inelastic scattering cross-sections, and the resonance parameters of neutrons are very fully covered. On the other ha the data on the characteristics of fissionable nuclei, fur example, are very incomplete, while the energy dependences of total cross-sections are not given at all. The extent to which the available information is analysed also varie For example, the resonance parameters given were obtained by averaging all the available data, but on inelastic scattering spectra and cross-sections only th data as measured by different authors are given, without a critical discussion of them. Apart from the results of measurements of nuclear data and their
analyais, the Bulletin contains information on the mothode used for calculatines cross-sections and tor analyeine experimental data, and also on certain other aspects of tho determination or mactical uso of nuclear physical oonstants.

The presont facue uses more or Less generally accepted terminology and notation, and thorefore no li.t of symbols or definitions is given. In view of tho differences in notation and torminoloEy uood in different soientific organifations, it is proposed subsequently to undortako a retional unification of symbols and tormis.

The Bullutin is produced by the Soientific and Tochnioal Information Bureau of the Physics and Power Institute of the USSR State Committee on the Utilizatio: of Atomic Energy.

#  OF WBUMONS WITH WUCLEI 

1. New data on the interaction of slow neutrons with a substance ..... 6 ..... 6
2. New data on thermal-neutron capture, and scattering cross-sections for elements with $Z \leqslant 91$ ..... 14 ..... 10
3. New data on resonance parametors ..... 18 ..... 11
4. New experimental data on radiative capture cross-sections and resonance integrals of neutron absorption ..... 43 ..... 12
5. Cross-sections of neutron reactions accompanied by the escape of charged particlos 83 ..... 14
6. Blastic scattering of neutrons ..... 105 ..... 16
7. New data on inelastic scattoring of neutrons ..... 210 ..... 20
8. Some new data on the characteristics of fissionable muclei ..... 259 ..... 22
9. Investigations of delayed neutrons ..... 266 ..... 24
10. Resonance structure of total cross-sections of a number of elements for intermediate and fast neutrons ..... 274 ..... 28
PARI II
RBACTOR CONSTANTS
11. Cross-sections averaged over the Maxwell spectrum ..... 284 ..... 30
12. Addition to "Group Constints for Designing IVuclear Reactors" ..... 297 ..... 31Pege
(of Russian (of Engl original) translat
13. Tables of coefficients for determining group parameters of anisotrooy of elastic scattering of neutrons ..... 307 ..... 33
14. Groüp crosismesotions of some nuclear reactions used for deteeting neutrons ..... 372 ..... 36
15. Tmpirical constants usod in caloulating radiation shielding for nucloar roactors 376 ..... 39
16. Critical parameters and nuclear safoty ..... 385 ..... 45
PART III
METHODOLOGICAI, QUESTIONS
1...Calculating nelutron cross-sections from the optical model using a computer ..... 402 ..... 53
17. Analysis of data obtained using a fast- neutron single-crystal scintillation spectrometer ..... 4.2 ..... 63

## PARTI I

PAFAMMERRS OF ELEMEHTARY JITERACTIONS OP NEUTRONS WITH NUGLHE
I. Nov data on the intoraction of slow noutrons with a substance

1. Gonoralized spectrum of normal osoillations for $\mathrm{H}_{2} \mathrm{O}$ and $\mathrm{D}_{2} \mathrm{O}$

Yu. V. Sokolov and T. F. Turchin

The doublemdifferential crossmsection for scattering of slow neutrons may be written in the form [1]
where $S(\vec{x}, \omega)$ is the scattering law and $\vec{x}=\vec{R}_{R}-\vec{R}_{0}: \omega=\left(J_{0}-\mathrm{E}\right) / \mathrm{h}$. Using the concept of the symmetrizod socatering lav $S(\vec{x}, \omega)$, related to $S(\vec{x}, \omega)$ by the equation
formula (1) may be presonted. in the form

If the scattering system has no separato states in the macroscopic sense (liquid, gas, semi-crystal), the scattering law will not depend on the direction of $\vec{x}$. Complete information on the soattering cross-sections is then contained in one function of two positive arguments $\widetilde{S}\left(x^{2}, \omega\right)$. This is a basic factor in processing and presenting experimental data, and was first used for this purpose by Egelstaff [2]. Since the double-differential scattering oross-section, measured experimentally, depends on thres variables, 巴 $, F, \theta$, by passing on to $\widetilde{S}\left(x^{2}, w\right)$ (a function of two variables), wo incruase the density of the experimental points on the eraphs of the relationshins required, and are able to countercheck the accuracy of the experiment in a more pucoinct form.

In most cases a rough approximation is adequate for reactor design [1]. In this approximation, the scattering law for a systom of $N$ identical atoms takes the form
where $X\left(x^{2}, t\right)$ is the Fourier transform of the autocorrelation function $G_{s}(\vec{r}, t)$ 。

For high and low values of time $t$, the function $X\left(s_{r}^{2}, t\right)$ takes the Gaussian form

For an ideal (mono-atomic) gas, a cubic crystal, or a liquid on the continuous diffusion model, equation. (5) is valid for any value of $t$ (the function $\Gamma(t)$ differs of course from ges to crystal and from crystal to liquid). For other scattering systems, equation (5) (for arbitrary $t$ values) should be regarded as a (Gaussian) approximation.

Following Egelstaff [8], wo take as a basis the symmetrized scattering Law $\widetilde{S}\left(x^{2}, \omega\right)$ with dimensionless arguments
( $T$ is the Kelvin temperature in energy units)

We designate
where $S_{q}(\alpha, B)$ is the Gaussian part of the scattering law, corresponding to the function $X\left(x^{2}, t\right)$ in the form shown in (5), and $S_{n}(\alpha, B)$ is a non-Gaussian correction.

Using the experimental data on the scattering law, it is possible to determine $I t$, and to calculate the Gaussian part of the scattering law $S_{q}(\alpha, B)$ with arbitrary $\alpha$ and $B$ values.

Introducing the dimensionless real function
the scattoring law $S(\alpha, \beta)$ may be written in the form

Using double integration by parts, we obtain
(If, when $t^{+\infty}, W\left(t^{\prime}\right)$ does not tend to infinity, it is necessary before integrating by parts to separate the multiplier .........).

Schofield $[9]$ has shown that at low a values the non-Gaussian number is proportioral to $\alpha^{2}$. Consequently

We determins the function $\rho(B)$.

Then reverse Fourier transformation gives
since $W\left(t^{\prime}\right)$ is a real function of $t^{\prime}$ 。
It can be shown [1] that for a cubic crystal
where ........... is the spectrum obtained with normal oscillations of the crystal in temperature units.

In the case of an arbitrary scattering system we may introduce, by analogy with (16), the generalized spectrum of normal oscillations
which is, broadly speaking, temperature-dependent.
It is not difficult $[1]$ to obtain an expression for $\mathbb{W}\left(t^{\prime}\right)$. This takes the form

Since to calculate group constants it is sufficient to know the function (B), the latter is determined from the experimental data on the doubledifferential cross-sections by extrapolation in accordance with (14). This issue of the Bulletin gives the $\mathrm{Q}(\mathrm{B})$ functions for $\mathrm{H}_{2} \mathrm{O}$ and $\mathrm{D}_{2} \mathrm{O}$ taken from references [10][11].
. . . . . . . . . . .(Bibliography)
2. Conditions determining the course of the radiative capture and fission cross-sections of certain elements in the thermal energy range

> V. N. Artamkin

In calculating thermalization effects, it is convenient to present the energy dependonce of the capture and fission cross-sections in the form
where $n$ is the number of resonances making a pronounced contribution to the crosssection in the thermal range。 Inter-resonance interference is disregarded.

For elements whose cross-section obeys the law $\frac{l}{v}$, only one component - a remains.

The table gives values of the coefficients $a, o_{i}$ and $e_{i}$ for a number of elements [1]. The cross-sections obtained by using them differ from the data in reference [2] by less than $0.25 \%$ for energies lower than 0.2 eV, less than $1 \%$ for $0.2-0.4 \mathrm{eV}$, and perhaps a little more for energies above 0.4 eV . . . . . . . . . . . . (Bibliography and Tables)
II. New data on thermal-neutron capture and scattering crose-sections for olemente with $\% \alpha_{0} 91$
I).A. Yardashev

III. Parameters of isolated resomanco levels
.. $\%$.M. Zakharova and $A . V$. Malyshev.

The tables given here have been compiled using the same assumptions as those in the second edition of the Directory $[46]$. Partial widths obtained in recont work have been averaged with tho data in the Direotory, if it could be definitoly established that they belonged to the rosonance in question, and if the discrep. ancies did not exceed the margins of error indicated. In other cases only the data of the latest work are given.

The parameters givon in the tables for resonances for fissionable materials were obtained by one-level analysis. If the data on the total moments of the resonances were contradictory, the results preferred in most cases were those obtained by experiment with polarized neutrons on oriented nuclei. It should be noted that because of the separate averaging of the partial widths, they may sometimes not agree with each other vithin the limits of the indicated margins of error. . The data of some new studies are not given, since the information contained in them is not complete.

- . . . . . . . . . . . . . (Tables and Bibliography)


## IV . Now axporimontul dutr on radjutive ourture ersom-moctions

 and rosonincs intograls of noution abisorjtionYu.Yu, ghavanoki ot al.

Tho radjativo cuptura axpmanootions and wosmanso intograla of noutron absorption aro given only for noumciamionable olononti. Fiamionable olemontre will bo doajt with in tho nost insuo of this mullotin.
 forn of graphs and tables, whioh jnoludo tho posulta of mownomentr publishod up to Ifay 2964.

Most of the oxperimontial data woro obtained by rocordine the capturo $\gamma$-rayri. Among thom aro the data of F.L. Shapixo ctial.....
-••
... Yu.Yz. Staviscly ot al.....
and J.iL. Wackiin and J.H. Gibboni; ...
The mothods and results of tho motruremonts are not discussod in each individual case, as this is done in tho literature cited. For most olomonts, the data arree with oach other in overlapring onergy ranges, in apito of tho difioronces in measuring mothods and onerey reselutions. It should, howover, bo noted that ior a number of eloments there is a discrepancy botwoon the results obtainod from different work usine the same mothods, and also a aystematio disorepancy betwoan the activation measurements and moasimoments of rny bj recordine tho capture $\gamma-r a y s$. This discrepancy should obviously not be resurded as a matter of chanco, although its nature is not yot clour.

The diagrams show tho capture cross-sections $s_{n}$, we function of tho onerim of the bombarding neutron. In a number of casoe (in the work of shapiro ot al.) the moasurements wero made on spocinens of dirfowont thicknossose This makos it possible to aswess the decreo oi solf"rhiolding of tho sapturo crosemection in the resonanoo range, and to detornino the enerey range where self-shielding becoracs unimportant.

For the eloments for which new meaturemonts over a wido wange of energies are lacking, the values of the capture crose-sections for monokinctic neutrone are givon in Table $I$, which also includes the $\sigma_{n \gamma}$ of Na and $K$, as measured on the fiseion spectrum.

Tabjo II givos tho results of activation moursuremonts of $\sigma_{n \gamma}$ over wide upoctra whioh ane ontabliched din the whiolding of $B R-1$ and BR-e fert reactors (Sh - J.) with mean offoctino antore of $\sim 150 \mathrm{kov}$ and $\sim 30 \mathrm{keV}$ respoctively。 Wido variations from the average rerf values aro murked with an asterisko some of tho rosultr appowring in Table 3 havo already bean published [L-3].

To obtain tho absolute values of ony a ony value for hum of $940 \pm 140 \mathrm{mb}$ measurod by trancmiscion in ophexjoal soomotry (for $E_{e i f}=30 \mathrm{keV}$ ) - and a valuo Of 1.74 b af tho fisrion cross-aeotion of P1 239 (for Efoff $=150$ keV) were used as supporting oross-aotions.

TabloIII collates the data on ahsorption resonance integrals $I_{y}$ not included - In "Nuclear Pinysical Constants" by IoV. Gordeevet al. Column 2 ohows the valuos of' $I_{\gamma}$ in barns, as obtained by diroct moasuremont and also as estimatad by the uuthors of the original papcre on the becia of their measurements of capture cros suctions (..............).

Column 3 indicatos tho hulf--lifo in cases when measuroment aas made by tho activation mothod. Column 4-Commonts - indicabes which cnorgy renge contributc ( to tho resonance integral eiver. Tho absenco of comment indicatos that the total rosonanco integral is given。

- . . . . . . . . . . (Diagrams, Tables and Bibliography)
V. Cross-sections of neution reactions accompanied by the oscape of charced particles

L.P.Abagyan, Som. Zatharova and M.N. Nikolaov

This section is a compilution of the experimentel data hitherto published on the cross-sections of neutron reactions accompanied by the escape of charged particles, for the elements He, Li; Be, B, C, N, O, F, No, Na and M.

Tho results aro given in tho form of graphs and tablese The graphs generally shor the cross-sections of the $(n, p)$ and $(n, \alpha)$ reactions. If the reaction has an energy threshola, its value is also shown on the graph. In some cases, the values of the cross-sections for the fission spectrum are given for threshold reactions. These figures are of direct practical interest in calculating fast reactors.

For $0, O$ and Ne values given are those of the oross-sections of the ( $n, \alpha_{0}$ ), $\left(n, \alpha_{1}\right)$, etce reactions which lead to the formation of a residual nucieus in the ground, first, etc. excited statos.

It should be noted that the rosults of measurement of the cross-sections of the reactions studied agree, vithin the limits of experimental error, An exception is the cross-section of the $B^{10}(n, t) 2 \alpha$ reactiong in paper [ $[505$ this was measured by studying the tracks in emulsjons, and in paper [ $4-58]$ by recording the tritium yield by absolute calculation of B-activity. In spite of the difference in method, the absolute values of the cross-sections agree well. The results of paper [D-6I], in which the cross-soction was moasured by recording $\alpha$-particles in an ionization chamber, are approyimately one third as large in the 4.5-MeV energ. rarge. It is interesting to note that the cross-mection of the $\mathrm{F}^{19}(\mathrm{n}, \alpha) \mathrm{N}^{16}$ reaction as measured in the last montioned work is also considerably (as much as $50 \%$ ) lower than the results of other works, although in this case the discrepancy does not exceed the limits of experimental error.

In some cases the graphs of cross-sections obtained from inverse reactions are given.

Table I gives some supplementary data on measurenents of the cross-sections of various reactions accompanied by the escape of charged particles at an energy of 14 MeV , and also includes cross-sections for the fission spectrum and the reactor spectra; the shape of the latter is similar to that of the former in the high energy range.

It should be noted that data are available on the angular distributions of the charged particles formed in the reeotions discussed, bit these are not included in the present review.

The authors are grateful to In. H. Liskien and Ir. A. Paulsen of EURATOM for the information they kindly gave to $S . I$. Sukhoruchkin about the ( $n, p$ ) and ( $n, \alpha$ ) reactions on Mg and Na. The data they provided on some of the heavier isotopes will togethor with relevant additional information, bo included in the next issue of this Bulletin.

Table I


## VI. Dlastic scatterins of neutrons

N.O. Bazazgants, M.N. Nikolaey and V.I. Popor

This section gives the results of experimental work on the elastio scattering of neutrons.

Tables I - V contain the angular distributions of scattered. neutrons given in the form of coefficients of expansion in Legendre polynomials. Using these, it is possible to calculate, by the formula given in the tables, tho differential. oross-sections for any angle of scattering.

Tables VI - VIII give the differential crossmsections as a function of the angle of scattering. All the data in the above tables refer to mork publishod since 1962.

Figs. l-ll give experimental data on elastic scattering published in 1963-64 and also before, but not included in the standard work on angular distributions $[1,2]$.

Table IX gives the total elastic scattering cross-sections given by the authors of the corresponding papers, and also (marked with an astertsk) calculated by integrating the differential cross-sections over the total solid angle. When there is a disorepancy between the calculated cross-sections and those listed from $[92]$, as ${ }_{\text {tot }} \stackrel{H}{r}_{n}$ no the latter are given in brackets.

The fourth column of this table gives the average cosines of angular distribution, calculated by the formula

These are also given, as a function of the initial energy of the neutrons, in Figs. 22-16 for nuclei of lithium-6, lithium-7, beryllium, boron, carbon, nitrogen and oxygen. When thore are large discrepancies in the . . . . values obtained by analysing the data of different authors, only the most reliable figures are shown in the graphs, preference being given to work using more modern measuring techniques and a more correct mothod of analysing the experimental data.

Brief information on the methods used in the experimental programmes whose results are given in this paper is to be found in Table $X$.

Table XI makes it possible to convort the Jegendre polynomial coefficient for the expansion of the angular distribution of scattering in the centre-of-m gystom to a laboratory: system ol comordinates.

Graphs roprinted from the standard work on angular distributions $[1,2]$ follow; theso'give, in the most convenient rorm, all the data published up to Ootobor 2962. The presont paper thus comprisos tho results of all the experimental work publishod on tho angular distributions of alastically scattered noutrons up to May 1964 .

A completo list of tho litoreture uscd appears at tho end of tho areticle. . . . . . . . . . . . Tables $I-I X$ and Pigs. 1-16)

METHODS OF FXPBRIMENTAL WORK
Table $X$

| Paper | Method | Threshold energy of detector |  |  | Correction for multiple scattering | Correction <br> for angular <br> resclution |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| $(3,4)$ | Time of flight, threshold scintillator |  |  |  | Not introduced |  | Absolute cross-sections given with an accuracy of 15-20 ${ }^{f}$ |
| (5) |  |  |  |  | Introduced. | Assessod as lo. | $\cdots$ |
| (13) |  |  |  |  | Tot introduced | Introduced | Absolute cross-soutions given with an cocuracy of $15 \%$. |
| (37) | . |  |  |  | Not introduced | Not introducod | Relative oross-sections obtained and nomalized to theorctical curve |
| (38) | ```Time or fligght, mnular zeomotry, threshold sointillator``` |  |  |  | Introduced | Introducta | . |
| (44) | Time of fligeldt |  |  |  | Not invroduced | Not introduced. |  |
| (46) | Huclear emulsions |  |  |  |  |  |  |
| (52-53) | 河ilson Chamber |  |  |  | . |  | . . . |
| (54) | Annular liquid threshold scintillator |  |  |  |  |  | - |
| (55) | Threshold proportional counter and liquid scintillator |  |  |  | Introduced | Introduced |  |


| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| (56) | Threshold. scintillator |  |  |  | Introducod |  | Absolute crobs-sections given with an accuracy $\approx 20 \%$ |
| (67) | Threshold proportional counter |  |  |  | Introduced |  | - : |
| (77) | Annular <br> geometry <br> threshold <br> scintillator |  |  |  | Assessed as low |  | - |
| (37) | Boron countcr in a modorator |  |  |  | irot introduced |  |  |
| (89) | Annular <br> geomctry, <br> ionization <br> chamber. |  |  | . | Introduced. |  |  |

1
1
1
. . . . . . . . . . . (Table, Oraphs and Bibliography)

## VII. New data on inelastio soattoring of meutrons

## V. iM. Sluone viskaya

This section includer experinental f'iguroe for tho tollowines crosssections for inolastic interections, orusis-soctions for inolastic ocattoring; nuclear "tomperatures", angular distributions of inelastically poattered neutrons, oross-suctions fror oxcitation of lovele in the inolastio scottering of nerutrons, cross-scotjons for emission of grman rage in the inolastio soattering of neutrons, and spectra of the swatitored noutrons.

This material has for the most part boon obtimined during tho last two viars, and is therefore noti contained in the Direotory F58].

```
. . . . . . . . . . (Data fon lithium, berylifum,
```

    boron, eto.)
    ```
(page 255 of original)
```


## Methods of measurement

Neutron spectrometry was in most cases carriod out by the time-of-fligh'i ritinod $[1,2,4,6-9,17,18,22-24,26,28,29,31-33,37,41,46,47,49$, 52-55, 60, 61, 68 7 and by investigating the speotra of the recoil neutrons using photographic platos $[.57,64,70,727$, ionization chambers $[15,16,39]$ and scintillators $[36,40,45,69 \ldots \%$

Papers $[13]$ and $[27,7$ used dotootors with an oleotronic throshold.
Inelastic scattering has also boen studicd by invostigating the gamma reys emitted $[4,5,12,14,19: 25,54,35,50 ; 62,63.7$.

In paper $535 .{ }^{j}$ the cross-section for inolastic scattering on $\mathrm{Mg}^{24}$ is obtained relative to that for the mis 24 ( $n_{9} p$ ) Na ${ }^{24}$ roaction,

In paper [56] tho eross-section for excitation of the motastable stato of


In papers [3], [42], [43] and [67] to [71] the cross-sections for inolastic intoractions are determined as the differonces between the total cross-sections and the experimentally detormined cross-sections for elastic scattering.

Papers $\left[10^{\circ}\right],[46]$ and $[51]$ investigated the $n^{\prime}-\gamma$ correlation

```
    . . . . . . . . . . . (Bibliography)
```

VIII. Some now data on the characteristios of fissionable nuciei
i. Averafe number of prompt noutrons emitted on fission of $\mathrm{U}^{235}$. by neutrons with an unorgy of $0.1-2.8 \mathrm{EeV}$

GoI. Smirentin etal.
. . . . . . . . . . . . . (Table)

1) Measurements made by the method described in the article by Yu.A. Bljunkina et al., Fuclear Physics, 52, 648 (1954).
2) Measurements made by recording the coincidences botween a block of boron counters in paraffin and a fission chambur pleaced inside it containing $U^{235}$.
2. Average kinetic energy of fission fragments and average number of prompt neutrons in spontancous fission of $\operatorname{cn} 244$
V.I. Bolshov et al.

For the spontancous fission of $\mathrm{Cm}^{244}$ valuos vere determined for the average kinetic energy of the fission fragments ( $E_{k}=182.3 \pm 2.3$ Fiev), the width of distribution at half-height ( $\underset{\sim}{ } \bar{\xi}_{k}=24.8 \pm 2.5 \mathrm{HeV}$ ) and the average number of prompt neutrons per fission ( $\bar{v}\left(\mathrm{Gm}^{244}\right)=2.71 \pm 0.4$ ).

The kinctic energy of the fragments was measured using a dual ionization chamber with a grid, by comparison with the well-established figure $\overline{\mathbb{F}_{k}}=166.9 \pm 0.8$ Jif for the fission of $U^{235}$ with thermal neutronc.
$\bar{v} \mathrm{~cm}^{24.4}$ was measured relative to the value $\bar{v}\left(\mathrm{Pu}^{240}\right)=2.17 \pm 0.015$. The method. used to moasure $\bar{v}$ was that of rocording coincidencos between a neutron detoctor (a group of counters containing $D P_{3}$ in a paraftin block) and a fission ionization chamber. containing layers of $\mathrm{Cn}^{244}$ and $\mathrm{Pu}^{240}$. Tho work will bo describod in greator detail in the journal "Atomnaya mergiya" 1204.
3. Fission cross-sections of $\mathrm{T}^{233}, \mathrm{~T}^{235}$ and $\mathrm{Pu}^{239}$ in the neutron enercy range $0.3-2.5 \mathrm{MeV}$ and of Pvi40 iri the range $0.04-4.0 \mathrm{MeV}$

> GoN. Smirenrin et al.

```
(Tables)
```

$$
\begin{gathered}
\text { 4. Pission cross-sections of } \mathrm{Pa} 231 \text { and } \mathrm{Pu} 239 \text { in the } \\
\text { neutron onergy iange } 1.5-1500 \mathrm{keV} \\
\text { S.iT. Dubrovina and V.A. Shigin }
\end{gathered}
$$

Fig. I gives the fission crossmoctions of Pe ${ }^{231}$ in tho range $150-1700 \mathrm{koV}$.
The measuronents were mado on an electrostatic accelerator. The method of experiment is desoribed in $[1]$ and $[2]$. The absolute value of the fission cross-section was determined with an agonmay of $15 \%$

The authors have discovered three maxima in the curve for the fission crosssection of $\mathrm{Pa}^{231}$, at neutron energies of 330,550 ank 380 keV . Fis. 2 gives the fission cross-section of Pu ${ }^{239}$ in the neutron energy range $1.5-1250 \mathrm{koV}$. The measurements were again made on an eieotrostatic accelerator. The method of experiment is described in paper [I]. The absolute value of the fission crosssection was determined with en accuracy ur $10 \%$.

The dispersion of the neutron energies in measuring the fission oross-soction of $\mathrm{Pa}^{231} \mathrm{is} \pm 20 \mathrm{keV}$, for $\mathrm{Pu}{ }^{239} \pm 20-30 \mathrm{keV}$ at neutron energies of $\geqslant 200 \mathrm{keV}$, and at neutron cnergies of $100,30,6$, and $1.6 \mathrm{koV} 10,8,3$, and 0.8 kev respectively.

## IX. Investigations of delayed neutrons

B. P. Maksyutenko

A characteristic of this diceld of invostigation is the fact that the first attempts to calculate the probability of the omission of delayed noutrons were not.made until 14 years after the experimental discovery of their uxistence.

This is explained by the insufficiontly rapid acoumulation of material, as a result of considorable difficultios in uxporimenting, insjuding low intensity of yield, short lifetimes, and laborious mathematical troatmont.
(1) Groups and identification

Theorotical calculations [I, 27 predict that the precursors of delayod neutrons are the fission fragments lying close to the areas with closed neutron sliells of 50 and 82 neutrons, occupying the left and right slopes of the peaks of the double-humped curve of mass distribution (light and hoavy fragments respectively). A possible set contains about 50. The main contributors must be isotopes of bromine, iodino, rubidium and ci:esium, The absolute values of the yield as celculated in $[1]$ and $[2]$ sometines differ by one order of magritude and cannot be considered accurata enough.

Wathematical analysis of the decay curvo $[3]$ has established that all elements and isotopos subjectod to fission by thermel neutrons and fissionspectrum neutrons give rise to six groups of delay $\Rightarrow$ d neutrons with half-lives of $55,22,6,2,0.5$ and 0.2 seconds. Ghemical reparition $[4]$ showed a slightly larger number of groups, with half-lives dilfering from the above. Using fixed crituria of selection, Keepin [1] established for each of the mathematically determined groups a set of precursors, either from among those identified chemically or postulated on the basis of theoretical calculations (Table I). A study of dolayod neutrons in tho :pontaneous fiesion of oalifornium $=252$ [5] showed that the groups with a half-life of 55 and 6 seconds had disappeared. Since tho groups corrosponding to the light-woight peak must disappear - because of its displacement for elervents of highex atomic weight we must conclude that bromine-88 cannot be a contributor to the second group, i。e. the precursor with $T \sim 15.5$ seconds must be a heavy fragment, iodine-138 cannot be a main contributor to the third group, etc. The chemical ideniification [4] must therefore be considered as for the nost part erroneous, nor can too
much reliance bo placed on what the same paper says regarding the quantitative proportions between the groups. Only bromine- 87 and ioding-j. 37 can be regarded as reliably iduntifiod. Howover, it should not be thousht that the chemists' work has boen in vain. It has shown that there may be more contributors than mathematioal breakdown of the decay curve suggestis. Unfortunately, even with high statistical accuracy, standard inathomatical methods cannot separate more than seven to eight groupse This is because when detorinining both the halflives and the initial intensities of the groups, 14 to 16 parameters must be determined. The soraration of groups close to oach other in half-life and relative contribution is an especially difficult task, requiring, according to our calculations, a statistical accuracy unattainable with existing neutron fluxes. The combined efforts of chemists and mathematicians might improve the situation. If chemists can reliably establish the half-lives (and this task is a simpler one, since aither ono group is separated in the pure form, or only two need be separated), the number of parameters to be determined for mathematical analysis of the curve can be halved, and. the contribution of more groups can consequently bo determined. The statistical accuracy at present at our disposal permits the separation of groups with half-lives of 15.5 and 24 seconds. We have made these calculations for plutonium-239 and isotopes of uranium $[6,7$ and this paper].
(2) Empirical laws

The ampirical laws obtained up to the present time may be summarized as follows:

1. For isotopes of uranium and plutonium $[1,8]$, und for one and the same energy of fission-inducing neutrons, the total absolute yiold of delayed neutrons increases with the increase in the $m$. $\sim$ number (Fig. 1).
2. On passing from uranium-238 to plutonium-239, there is a sharp drop in total yield. The dependence of the yield on the $Z$ of the nucleus is thus greater than on A .
3. Yields of individual groups show tho same dopendence on $Z$ and $A$ throughout the group. An exception is the group with $T=55$ seconds, in which there is an opposite tendency (Fig. 2).

- 4. Wo havo studad tha way in whioh tho ratio botwoon tho ytolda of' individual groups (yjold of fisect eroup taleon as unity) charges with a chango in tho enorgy of tho noutrong cousing limston she why in which the ratio changes, is shown for uranium-238 in Fíe. ; and Tralo TIT, For most groupe thu relative yields (i.0. rolative to fitst group) dooruaso with in increase in enerey (this occurs also for uraniur-235 and flutonitum-239 (Tublot III and IV)). In the enorgy range where tho ( $n$, nf) rooction begins thore jefor uranium-2 38 a sharp inorease in melative yiolds. To aru at presont taking mocisuromonte for other fiseionable mului in the same range of enorgios.
(pages 268-270 of' originel)

Table I

| No. | $\begin{gathered} T \\ \mathrm{~s} \in \mathrm{c} \end{gathered}$ | Precursors of groups (1) |
| :---: | :---: | :---: |
|  |  | Bromine-87 <br> Iodine-137 <br> Bromine-88 |
|  |  | Iodine-138 (bromine-89, bromine-90) <br> Iodine-1.39, caesium-144, bromine-91, bromine-92 <br> Iodine-140 (bromine-92) <br> Bromine-93, rubidium-97 |

Table II
Uraniun-238
Relative Yields

- . . . . . . . . . (Table)

Rolative yiolds of dolayod noutrons (uraritum-235)


Tuble IV
Plutoniun-239

. . . . . . . . . . . Kemainder of Table IV
Figures and Bibliography)

## Y. Resonance structuro of total cross-sections of a number of elements for intermediato and fast noutrons <br> M.M. Nikolaev etal.

Belov are given the charactoristics of the resonence structure of the total
 Mo, Cd, $W$, $\mathrm{Pd}, \mathrm{Bi}, \mathrm{U}$ and $\mathbb{T}$ ), these characteristics being obtained by enalysis of the transmission curves measurod in a good goometry to an attenuation of $T_{m i n} \simeq 0.01-0.001$. The struoture of tho total cross-section is described in terms of the function $P(\sigma)$ - tho probahility of finding in tho invostigated neutron energy rango a value of the total oross-section equal to $\sigma_{0}$. This function is represented approximately in the form of a woighted supor-position of the standardized © furnctions:

The coefficients $a_{n}$ and the cross-sections $g_{n}$ are unambiguously determined by analysing the transmission curves $T(t)$ by the least squares method according to the form $\ldots \ldots \ldots$ if mand $T_{m i n}$ are fized.

Knowing the function $P(o)$, it is possible to find the average values of any functions from the total cross-soction ......... . Apart from the magnitudes of $a_{n}$ and $\sigma_{n}$, Table I gives the average characteristics $\langle\sigma\rangle$ and $\left\langle\frac{l}{\sigma}\right\rangle^{-1}$ (the angular brackets denote averaging over the intervals indicated). The value of the product or $\langle\sigma\rangle$ and $\left\langle\frac{1}{\sigma}\right\rangle$, which is a convenient characteristic of oross-section structure, is also given.

Table I gives the preliminaxy results of such a breakdown, obtained approximately. in graphioal form.... Accurate analysis. will be.corriod out on a computer. It should also be noted that accurate analysis carried out for the case of wanium (Tablc II) shoved that, at least is the case of a not too considerable cross-section structure $\left(\langle\sigma\rangle\left\langle\frac{l}{\sigma}\right\rangle \sim 1\right)$, the approxinate remalts give a reasonable ostimato of the size of the real structure of the total cross-seotion. The last column of Table II gives the value of the correlation coofficient for the values of the two oross-sections which describo the resonance struoture of the total cross-section of uranium. This figure must be taken into account in calculating errors in the calculated average characteristics. Tho exrors given in Table II do not take into account the effect of indetcrminacy in the thichness of the specimens, nor the offect of scattering onto the detector. A detailed description of the experimental method for measuring the
structure of total cross-sections, and of the methods of analysing the data given here, appears in papers $[1]$ to $[4]$.

PART II

## REACTOR CONSTANTS

## I. Cross-sections averased ovor the Maxwoll spectrum

A.N. Galanin et al.

Tables I-XII give the crossmections of uranium and plutonium isotopes averaged over the Maxwell spectrum, which are used in tho 2-group mothod of caloulating nuclear reactors. They aro givon as a function of the neutron gas temperature and of the energy corresponding to tho boundary whore the inaxwoll and Fermi spectra join. The energy depondence of $\sigma_{a}, \sigma_{f} \eta$ and $\alpha$, and the resonance parameters were taken from papers [l-4]. The cross-sections are normelized to the agreed international values of aross-sections at $2200 \mathrm{~m} / \mathrm{soc}$ given in papers [4-5].
II. Addition to "Group Gonstants For Dosigning Muciear Reactors" [1, 4_7
L.P. Abagyan etal.

Some additions to the $26-$ group system of constants $[1]$ are given below. The first is $u$ systom of constants for cerium (Ce), which is used in fast reactors with Iiquid notal plutonium fucl. Group constants are also given for the steels most widely used in reactor construction (EYa-IT-73\% Te, $18 \% \mathrm{Cr}, 9 \% \mathrm{Ni}$ and EI- 874 - $67 \% \mathrm{FO}, 15 \% \mathrm{Cr}, 15 \% \mathrm{Ni}, 3 \% \mathrm{MO})$ 。

Gome corrections to tho values of the group parameters of $\mathrm{Fe}, \mathrm{Ni}, \mathrm{U} 23$ and $P_{1}{ }^{239}$ are then givens those are based on multi-group calculations of macroscopic tests on reactors [2] using the system of constants [1], and on new experimental and theorotical data.

These corrections are incorporated in the American odition $[4]$ of the 26-group sys tem of constants.

The system of notation in the group constant tables given here is that used. $\operatorname{in}[1]$ 。

Firnally, data are given which facilitate the introduction into the slowingdown cross-sections of corrections for the shape of the intra-group spectrum.

In the group constant tables, the cross-section of elastic ilowing-down
contains the correction
which differs from unity when the intra-group spectrum is not a Fermi spectrum. $b_{i}(\xi)$ can be calculated by quadratic interpolation of the group spectrunt

Here $\varphi_{i}$ is the integral flux of neutrons in the $i^{\text {th }}$ group obtained as a first approximation (with uncorroctod slowing-down cross-sections).

The coefficients $A_{i}, P_{i}$ and $O_{i}$ given below were determined in such a way that, by extrapolation of the shape of the neutron spectrum in the region of the
[4] L.F. Abagyan etal., "Group Constants for Dosigning Nuclear Reactors",
Consultants Bureau Enterprises Inc., New York (in press).
$i^{\text {th }}$ group of quadratic form (3), the integral neutron fluxes in the (i-1) ${ }^{\text {th }}$ i $^{\text {th }}$ and $(i+1)^{\text {th }}$ groups are retained.

The coefficients for the first two groups are not given, since quadratic extrapolation of tha flux is not well applicable to them.

Furthermore, the reactor spectra in this energy range are always close to the fission spectrum, which was used in paper [l] in claculating the slowing-down cross-sections of groups $1-3$.

Paper [I], in calculating the slowing-down cross-sections in the third group, accordingly introduced correcting multipliers taking into account the difference between the spectrum used ard the Fermi spectrum (taken in the lower energy groups)

The coefficients $A, B$ and $C$ given here for the third group take into account the fact that in order to obtain an accurate slowing-down cross-section it is sufficient to multiply the slowing-down cross-sections given in the table for the third group by $b_{3}$, calculated using the coefficients given.

# III. Tables of coefficients for detormining group parameters of anisotropy of alestio scattering of neutrons 

## M. N. Mikolaev et al.

To carry out accurata celdulations of reactor systems and radiation shielding, it is often necessery to take into account the anisotropy of neutron soattering with grestor eocuracy then is the oase in the normally used transport approximation with isotropio transiers from group to group. To carry out such calculations it is necessary to determine supplementary group parameters, namely the moments of the cross-section for soattering thet results in the passage oif neutrons fiom one energy group to another or in leaving them in the same group. The values for these parameters depend on the width of the onergy groups used in the caloulation, on the intra-group spectrum of the neutrons, and also on the form of the angular distribution of the scattered neutrons.

For elastic scatterine, tho expressions for these values may be written in the form
where
is the cosine of the angle of scattering in the leboratory system of co-ordinates,
$\mu^{\prime}$ is the cosine of the angle of scattering in the centre-of-inertia system,
$\omega_{m}^{c o m o}\left(A^{\prime}\right)$ is the Legendre poiynomial coefficient for the analysis of the elastic scattering indicatrix in the centre-of-inertia system,
$\sigma_{e}$ is the cross-section for ulastic scattering,
$E^{\prime}$ is the initial energy of the neutron,

$\widetilde{I}$ and $\widetilde{\mathbb{S}}_{\ell-1}$ detormine the boundaries of the energy range in group $\ell$ from which clastic slowing-iown to group $j$ is possible,
$\widetilde{T}_{j}$ and. $\tilde{\mathbb{T}}_{j-1}$ are the boundaries of the onergy rance in grour $j$ into which the elastio slowing-down of noutroms from groun take place, $P_{m}(\mu)$ are Legendre polynomials of the in th orter. $\varphi_{n}\left(E^{\prime}\right)$ is the spectrum of the $n^{\text {th }}$ harmonic of the neutron flux.

The form of this spectrum is correlated with the enerey dependence of the
 expressions given in [J.]. This correlation leads to an effect of rosonance self-shielding of the slowing-down cross-section and of the parameters of anisotropy of scattering $[1]$. To separato this effect, which is linked with rapid changes of the neutron spectrum and tho oross-sections, we replece the rapidly changing functions
 substitute the results of this averaging for the average values in the whole energy range of group $\ell$, which makes it vasior to allow for the dependence of the group parameters determining the slowing-down of the neutrons on the form of the intra-group spectrum, smoothed out as to its resonanco properties [2]. The formula for this averaging are given in papors $[7]$ and $[2]$. As a result of this operation, expression (1) takes the form

In the second integral of formula (3), we now replace integration with respect to $E$ by integration with respect to $\mu$, using relationship (2). Transferring to a laboratory system of co-ordinates in the analysis of the scattering indicatrix, we obtain
where

Here....... is tine $m^{\text {th }}$ harmonic of the elastic scattoring indicatrix in a laboratory system of co-ordinates, averaged according to the spectrum of the $n^{\text {th }}$ harmonic of the neutron flux in group $\ell$ 。
$\varphi_{n}\left({ }^{\prime}{ }^{\prime}\right)$ Is the neutron spectrum smoothed out as to resonance charecteristics. The form of this spectrum must be fixed beforehand when compiling group constants.

The tables reproduced below give the coefficients $A \rightarrow j$ for a wido range of elements used in reactor construction, calculated by formula (5) on an in-20 computer [3]. These coefficionts can in principle be useci to calculate the parameters of anisotropy of soattering, which must be known in order to make reactor calculations in the P-5 anproximation. In cases where this calculation can be made, the degree of accuracy with which the anisotropy of scattering can be takon into account (iote the number of terms of the anaiysis of the scattering indicatrix.) corresponds to the $\mathrm{P}-7$ approximation.

The group intervals used in the alculations coincide with those used in paper [2]. The neutron spectrum $\varphi\left(E^{\prime}\right)$ is also taken, in accordance with the same paper, as equal to the fiosion spectrun in groups 1 and 3 and to the Fermi spectrum in the lower energy range. The programe of calculations also envisaged the possibility of finding the coofficients $\omega_{m}^{l}$ for set angular distributions, and also of determining $\bar{W}_{n} \ell \rightarrow j$. No provision is made in this programme, however, for taking into account the resonance self-shielding of tho cross-sections. In view of the incomplete nature of the analysis of the experimental data on the angular distributions of elastically scattered neutrons and on the resonance structure of the differontial scattering cross-sections; the values of $\mathrm{T}_{\mathrm{n}}^{\ell \rightarrow j}$ are not given here.

For nuclei with comparativoly luw mass numbers $A$, the coefficients $A n-j$ are given separately for each elemont, For heavy nuclei, they are given for groups of olements with $A$ values olose to one another.

The values of $l$ and $j$ are given above cach table. In cases where the coefficients $A_{n m}^{l \rightarrow j}$ coincide for lifferent values of $l$ and $j$, a single table is given above which are indicated all the values of $\ell$ and $j$.

In tho case of heavy nuclei it is possible when calculating equation (4) to use only two terms, corresponding to the values $m=n$ and $m=n+1$. To save space, a slightly different layout for presenting the data is used in this case。
(Bibliography and m:es)

## IV. Group cross-sections of some nuclear reactions used for detecting neatrons <br> V.I. Golubev et al.

The most widely used method of checking the accuracy of multigroup reactor calculations is to comparo the experimental distributions or the rates of various roactions having different aross-section vs. energy variations vith the calculated distributions, and also to compare the calculated and oxperimental ratios of the cross-sections of these reactions on reactor spectra.

To be able to perform the calculations for a given type of experiment, we must have a set of the average group cross-sectjons used for testing tho reactions. The number of groups in this set, and also their energy boundaries, must correspond to the breakdow used in calculating nuclear flux.

The most complete system of constants at present in use for reactor calculations is the 26-group system [1]. The group cross-sections given here, for the reactions normally usod for macroscopic tests on reactors, presume the use of this system of constants for calculating neutron fluxes. Whore the cross-seotions of reactions used for dotocting neutrons are given in paper $[1]$, no attempt is. therefore made to review them hore.

The initial data used to compile the tables of the group cross-sections were the published results of individual small-scalo experiments, and also information on the parameters of the rosonance levels investigated. The papers used to compile the tables given below are listed in roference [2].

In the energy ranges where sufficient axperimental data were available, the average cross-sections were obtained from smooth curves passing through the experimental points.

In ranges where there was sufficient information on the parameters of the resonance levels, the resonance capture cross-sections were calculated by adding the integrals of the separate resonances composing the sroup.

When there were in a particular energy range neither experimental data nox information on the parameters of individual resonances, the radiative capture cross-sections were calculated on the basis of the average resonance parameters. In this case the energy dependence of the contributions made to the capture
cross-section by neutrons with different ortbital movements was taken into account.

The cross-sections of the $\mathrm{Np}^{237}(\mathrm{n}, \mathrm{f})$ reaction at energies above 10 keV were obtained from the average of the knowm experimental data. At lower energies, the cross-section was determined from the theory of sub-barrier fission and from the available data on resonance neutrons. In the onersy range $0.2-1$ eV the figure given is the higher estimate for the fission cross-section of Np 237 according to the parameters of a rosonance at 0.49 eJ.

Apart from the average group cross-sections, the tables also contain the calculated values for resonance integrals and cross-sections for the fission spectrum. Both these sets of figures are compared with experinental results. It should be noted that all the experimental data used in this work have an accuracy not exceeding $5 \%$. The accuracy of our knowledge of the parameters of resonanco levels is, with a fow exceptions, even lower. Therefore, when experimental and calculated distributions of nuclear reaction ratos are compared, agreement to within $10-20 \%$ should be considered satisfactory, the more so since in calculatine neutron fluxes the constants used are generally of the same degree of accuracy (especially when the offect of resonance self-shielding of the cross-sections is great).

The proposed average cross-sections of nuclear reactions have been checked in macroscopic tests on a BR-1 reactor [3].
. . . . . . . . . . (Bibliography and Table)

# Cross-sections for the fission spectrum 

Mieasured
Calculated

Rosonance integrals of capturo
Measured
Calculated.

## V. Empirical constants used in calculating radiation shielding for nuchear reactors

1. Coeffioients of secondary gamna radiation
S.P. Belov and Yu.A. Kazansky

The intensity or the gamma-radiation caused by the radiative capturc of neutrons in the shielding (secondary or capture gamma radiation) is conventionally normalized to the all-mave integral neutron flux behind the shielding. The coefficient of secondary gamma-radiation is determined as a ratio of the total number of gamma quanta to the total number of neutrons leaving the shielding ( $Q B$ ) [I].

Using the coefficient of secondary radiation, it is possible to determine the gamma flux $J(R, \vartheta)$ at a point behind the shielding with co-ordinates $\Omega$ and $\theta$ : $J(R, \vartheta)=B Q b G(R, \vartheta)$ whore $G(R, \theta)$ is the geonetrical factor of attenuation, which can be calculated comparatively easily in each particular case $[1,2,3]$.

As has been shown in rofenences $[1]$ and $[4]$, the values of 3 for a shielding thickress of $150 .-200 \mathrm{~g} / \mathrm{cn}^{2}$ are in practice constant, if the length of the mean Iree path is less than the analocous figure for the neutrons of the leading group, and depend on the physical properties of the mediun, $i$. $e$. the linoar coefficient of gemma attenuation, the cross-sections of interaction of the neutrons with the nuclei, eto. The coefficients of secondary gammaradiation can be experimentally determined without resorting to absolute measurement of gamma and neutron fluxes. The accuracy of the measurements of $B$ for gamma-rays with an energy of more than $4-6$ liev is $\sim 10 \%$. At lower energies the orror increases considerably as a result of the indeterminacy of the number of gamma quanta emitted on the capture of a neutron.

The table gives, in percentages, the experimental asymptotic values of the coefficionts of secondary. gamma-radiation for a number of matorials and two neutron sources $[I, 4,5](P o-\alpha-B e)$, and the spoctrum of the RIZ reactor $[5$.$] .$

The coefficients of secondary radiation are determined for gamma quanta with energies higher than $B_{\gamma}$, the values of which are given in the tablo.
. . . . . . ..... . . (Table and Bibliography)

# 2. Angulux distributjos.of intomity of scattorod ganma-ruyt on tho boundiary of a moniminfinito medium <br> Tu. A. Kakmelcy and E.B. Matubovich 

Tho angular distribution oll intensity from the gaman-ray unitiod by an isotropio print sounco on tho boundary of. a somi-infinite modium iss dotormined by tho exproscjon

Whore $\mathbb{E}_{0}$ iss tho onorgy of tho sourco, $P$ is tho distance betweon the source and the boundery of the medium, 0 is tho ancle botwoen the direction from the source to the observation point and tho direction of observition.

This distribution can bo rourecontod by an expression with ono experimentally determined paramoter $O_{c}^{T}$
where $I_{0}$ is tho intonsity of tho sourco, $\mu_{0}$ is the linear coofficiont of attenuation of the camma-rays from the sourco in the material of the medinm, Bos is the energy factor of accumulation for a point isotropic source in a medium of infinite extent. Ropresentation of $J \frac{T}{\vartheta}$ in tho form (2) is valid for the range of angles $5^{\circ}<090^{\circ}$ with an accuracy of the ordor of $10 \%$. The empirical magritude $\vartheta_{c}^{T}$ is indopendent of $R$ to an accuracy of up to $10 \%$ when $\mu l \infty 1$.

Tho oxperimental values of $\vartheta_{0}^{T}$ from papors $[1]$, $[2]$ and $[3]$ are given in the following table.

| Source energy | ${ }^{T}{ }_{c}^{\text {degrees }}$ |  |  |
| :---: | :---: | :---: | :---: |
|  | Medium |  |  |
|  | Wator | Iron | Lead |
| G. 411 MeV | - | $49 \pm 3$ |  |
| 1.25 LEV | $38 \pm ?$ | $33 \pm 2$ | - $19 \pm 1$ |
| 2.76 Mov | $30 \pm 3$ | - | - |

Whe errors talo into account a slight change in $\vartheta_{c}^{T}$ depending on $\mu_{0}$. The values of $\forall_{c}^{T}$ for intermediate $Z$ values of the medium can be obtained by Iinear interpolation.

For a plane monodireotional source, with normal inciumen on a barricr of thickness $d$, tho value of the intonsjity of radiation por unit solid angle may also be represented by the following oxpression
in which $J_{\vartheta}^{n}$ depends on one paraneter $\vartheta_{c}^{n}$
where $q_{E}$ is the energy emitted by a unit surface of the source and $B_{d}$ is the onergy factor of accumulation for a barrier of thickness $d\left(B_{d} \approx B_{\infty}\right)$. The formula is valid for $15<\vartheta<90^{\circ}$, and values of $\vartheta_{c}^{n}$ are independent of $\mu_{0} d$ to an accuracy of up to $10 \%$.

The experimental values of $\theta_{0}^{\mathrm{r}}$ obtained in papers $[4]$ to $[8]$ are given in the following table.

Values of $\vartheta_{c}^{n}$ in degrees

| Source <br> energy | Medium |  |  |
| :--- | :---: | :---: | :---: |
|  | Aluminium | Iron | Lead |
| 0.28 MeV | 40 |  | 32 |
| 0.411 MoV |  |  |  |
| 0.66 MoV | 32 |  | 14 |
| 1.25 MoV | 24 | 21 | 16 |
| 2.76 MeV | $21 \cdots$ | 19 | 15 |
| 4.0 MeV | 16.5 |  | 13 |

The error in the $\vartheta_{c}^{n}$ values is $\pm 10 \%$. Linear irterpolation according to $Z$ is permissible. In formulae (2) and (4) $\vartheta_{c}^{T}$ and $\vartheta_{c}^{n}$ are given in radians.

```
(Bibliography)
```

3. Some constants determining flux and dose rate of fast neutrons in air at different distances from the source
S.F. Degtyaryov and V.I. Kukhtevich

## A. Infinite air medium

If $R$ is the distance from the source to the detector, $\Sigma_{5}$ is the macroscopic scattering cross-section of air, $Q_{\text {, }}$ is the source intensity and $E_{0}$ is the initial energy of the neutrons, then the expression
where
is the flux of scattered neutrons, and is the fluti of dircot radiation (.............): sill be vilid for a point isotropic source and an isotropic detector.

Hxpression (1) is valid for $0 \leqslant k \leqslant 50 \mathrm{~m}$ and for initial neutron energies from 0.33 to 14 MeV .

For the same geometric conditions, if $\Sigma$ is the total macroscopic crossisection of interaction; then

Where $B\left(F_{0}\right)=0.195 \pm 0.02$ for $0.33 \leqslant E_{0} \leqslant 6 \mathrm{MeV}$ and $0.145 \pm 0.015$ for $7 \leqslant E_{0} \leqslant 14 \mathrm{MoV}, \mathrm{D}_{\mathrm{pas}}$ is the dose rate die to the scattered neutrons, and $\mathrm{D}_{\mathrm{n}}$ is the dose rate of tho direct radiation ( $\bar{D}_{n p}=\ldots .$. where , $_{0}$ is the coefficient converting : single neuṭron flux into dose rate).

The angular distribution from a point isotropic source, and the spatial: distribution from a.point monodirectionel source, are described"by the expressions
where $\vartheta$ is the angle of orientation of the monodirectional source or detector relative to the axis connecting thom.

For dose rate the expressions take the form

The accuracy of expressions (3) and (4) is $\pm 20 \%$ for distances of $0 \leqslant R \leqslant 50 \mathrm{~m}$. In (1) - (4) $R$ is expressed in $m s \Sigma_{t}$ in $m^{-1}$, and in (3) and (4) $\vartheta$ is expressed in degrees.

## B. Air-earth separation boundary

If $H$ is the equidistant height of the isotropic source and the isotropic detector above the earth's surface, and $R$ is the distance from the source to the detector, then
.
where
$R$ and $H$ are expressed in $m$, ............. in $m^{-1}$. The accuracy of expression (5) is $\pm 10 \%$ in an initial-neutron-energy range from 1 MoV to 5 MeV . The limits of applicability or (5) are $5 \leqslant 1 \mathrm{l} \leqslant 30 \mathrm{~m}$ and $1 \mathrm{~m} \leqslant \mathrm{H} \leqslant 30 \mathrm{~m}$. Expressions (1) - (5) are obtained from the results of papers [1]-[6].
. . . . . . . . . . . . (Bibliography)
4. Passafe of fast neutrons from a reactor through shiclding not containing hydrogen
E.I. Sinitsyn and S.G. Tsypin

In media not containing hydrogen, the functions of attenvation of a fast-
 can normally be approximated with sufficient accuracy by functions of the type
where $R$ is the thicknoss of tho shielding and $q$ is an empirical parameter equivalent to the reciprocal neutron relaxation length $\frac{l}{\lambda}$, which will be determined below.

The range of applicability of expression (1) is normally limitod to from 2 to $15-20$ mean free paths of the noutrons. With high shielding thickness, the effect of filtration of the neutrons by the shielding material may have a considerable effect on the relaxation length. In this range the relaxation length will be dotermined to an increasing extent by the minimum - for the energy range investigated - cross-section of interaction of the neutrons with the shielding material.

The following values are normally used as the parametor q:

[^0](1) The removal cross-sections $\Sigma_{\text {rem }}$, detorminod for the group of neutrons with energy $\mathrm{E}>3 \mathrm{MeV}[1]$;
(2) The oross-isections obtained from the reciprocal relaxation lengths $E_{\frac{1}{\lambda}}=\frac{1}{\lambda}$ for the group of neutrons with an energy $\mathrm{E}>3 \mathrm{MeV}[1]$;
(3) The asymptotic cross-sectiors $\Sigma_{\text {as }}$ obtained by solving the one-group kinctic equations using the exprossion
obtained in the transport approximation, using group constantes systems [3], [4_7 For the onergy groups 1.4 YeV to $\infty$ and 2.5 YhcV to $\infty$. In expression (2) the following symbols are useds $\Sigma_{\text {tr }}$ - the total transport cross-section in the group, and $\Sigma_{\text {tr }}^{s}$ - the transport scattering cross-section in the group. $\Sigma_{\text {if }}=\Sigma_{t r}^{s}+\Sigma_{y b}$, $\Sigma_{y b}$ being the cross-section for removai from tho group.

The table contains the mpiricel parameters ......................... ( $e$ is the density of the nuclei), taken from the numerous sources in the litorature. It can be soon from tho table that thesc parameters agree satisfactorily (the maximum deriation from the average does not excesd $10 \%$. This makes it possible to use th se date for ostimates of nuclear reactor shielding.
VI. Critical parameters and nuclear safety
13. G. Dubuvsky ot al.

The authors havo carried out a sories of critical experiments aimed at nuclear safety and the study of reactor physics. The resulta of some of these experiments are given below.

The experiments were conduoted with aqueous solutions of $\mathrm{UO}_{2}\left(\mathrm{NO}_{3}\right)_{2}$. The temperature of the solutions varied from 15 to $21^{\circ} \mathrm{C}$, and the number of nitrogen nuclei $Q_{N}$ was betwoon 3.0 and 3.1 times as large as the number of uranium nuclej $0_{u}$. The uranium concentration of the solution was varied from 40 to $500 \mathrm{~g} / \mathrm{I}$ 。

The experiments were carriod out on reactors in the form of spheres, cylinders and rectangular parallelipipeds made of stainless steel 1-1. 5 mm thick ( 3 :um for the parallelipipeds).

All the experiments may be classified in one of the following groups:

1. Critical parameters of reactors of different shapes.
2. Jfinciency of neutron absorbers.
3. Intersotion of sub-critical systems.

## 1. Critical parameters of reactors of different shapes

The dependence of the critical volumos of the solution and the critical mass of the uranium on uranium concentration was studied for reactors of different shapes with a water reflector and with no refloctor. The results of the experiments vith uranium of $90 \%$ enrichment are given in Figs. 1 and 2 , and those with uranium of $10 \%$ enrichment in Table I.

## 2. Efficienoy of neutron abscruers

Boron and cadmium absorbers in the form of rods and inserts were studied. (a) Rods

The absorbing rod was a oylindrical sheath of stainless steel containing either boron carbide powder with a density of $1.25 \mathrm{~g} / \mathrm{cm}^{3}$, or a cadmium tube 0.5 mm thick filled with water.

The dependence of the efficienuyof the rod on its diameter, the thickness of tho steel casing, the diameter of the core and the position of the rod in the core was studied for various concentrations of uraniun in the solution, for go\% enriched uranium.

The interference of two or moro rods as a function of the distance between them wius alsc studied.

The effectiveness of lattices of absorbent rods as a function of the lattice pitoh and the number of rods in the core wars studied.

Figs. 3-8 give some of the results of experiments vith rods and rod clusters. (b) Inserts

The absorbing inserts were two coaxial stainless steel cylinders with the absorbent placed between them.

Two types were investigated - "thin" unes in which the absorbent was either boron carbide powder with a density of $1.25 \mathrm{~g} / \mathrm{cm}^{3}, 6 \mathrm{~m}$ thick, or cadmium 0.5 mm thiok: and "thick" ones in which the abscrbent consisted of two 0.5 mm layers of cadinium on the cylinder walls, with either 25 or 50 mm of water in between.

The effioiency of the absorbing inserts as a function of the average radius of the insert and the thickness of the layer of water was studied for various concentrations of uranium in the solution.

Figs. 9-10 give some of the resulta of these experiments.
3. Interaction of sub-eritical systems.

Interaction was studied on reactor: in the shape of rectangular parallelipipeds with a 30 cm bese, and of cylinders 30 mm in diameter, for various concentrations of $90 \%$ enriched uraniura.

Figs. ll-13 give the results of sume of the experiments. The diagram shows the dependence of the volune of the solution in one reactor on the distance between reactors, on condition that all the reactors are oritical and the amount of solution is the same.in each.

The interaction of these reactor: through water, graphite and boron oarbide was also studied.

A semi－empirical methoc of calculating the intoractions of sub－critical reactors，known as the method of＂equivalent dimensions＂，was developed in the labordtory．lhis method consists assentially of replacing the whole systen －of reactors by a single reactor，determining the equivalont dimensions of this reactor and comparing the geonetrical specirication of the equivalent reactor with that of a reactor of the particular design in question．The formula used to determine the equivalent dimensions of the ractor is cequiv。 $=C[1+(n-1) \Omega \bar{l}$ ， where $C$ is the dimension of one sub－critical reactor in tho direction of inter－ action，$n$ is the number of interacting reactors in the direction of $C$ ，and $\Omega$ is the solid angle between two neighbouring reactors in the direction of inter－ action．

Figs．11－13 compare the results of calculations by the＂equivalent dimensions＂ method with experiment．

The interaction of a large number of sub－critical reactors of 6－litre capacity was also studied．The reactors were constituted by cylindrical glass vessels 18 cm in diameter and 24 cm high．The wall thickness was 0.5 cm and the concentration of uranium in the solution was $96 \mathrm{~g} / \mathrm{l}$ 。

The vessels ware arranged in sereral plancs at difforent distances fron each other，forming a three－aimensional network．The results of these experiments are given in lable II。

As can be seen from the diagrams，with a s！nall nuraber of reactors arranged in one plane the calculation onsures a $10-15 \%$ safety margin．In the case of three－ dimensional networks（lable II）this margin increases considerably，and may exceed $100 \%$ ．It omerges from the review peper $[I]$ that the accuracy of the proposed method is comparable with that of othor methods of calculating systems of interacting reactors；it is distinguished from them，however，by its consicer－ ably greater simplicity and convenience。

```
                                    (Bi)liography)
```

Table II

| $\begin{gathered} \text { Arrangement } \\ \text { containers } \end{gathered} g^{f}$ | No. of containers |  |  |
| :---: | :---: | :---: | :---: |
|  | Used | Critical | Saloulation. |
| In two planes | 23 | 23 | 12. |
| $\begin{aligned} & d_{\mathrm{x}}=1 \mathrm{~cm} \\ & d_{\mathrm{y}}=4.5 \mathrm{~cm} \\ & d_{\mathrm{z}}=12 \mathrm{~cm} \end{aligned}$ | In first plane $4 \times 3=12$ <br> In second plane $/ 4 \times 3 /-1=11$. |  |  |
| In three planes | 52 | $54 \pm 0.5$ | 18 |
| $\begin{gathered} d_{x}=d_{y}=6.5 \mathrm{~cm} \\ d_{X}=12 \mathrm{~cm} . \end{gathered}$ | In first plane $4 \times 4=16$ <br> In second plane $4 \times 5=20$ <br> In third plane $4 \times 4=16$ | /Extrapolation/ |  |
| In three planes | 39 | $39.5 \pm 0.3$ | 12. |
| $\begin{gathered} d_{x}=d_{y}=4.5 \mathrm{~cm} \\ d_{z}=12 \mathrm{~cm} \end{gathered}$ | In first plane $3 \times 4=12$ <br> In second plane $/ 3 \times 4 /+3=15$ <br> In third plane $3 \times 4=12$ | /Bxtrapolation/ |  |
| In four planes | 67 | $80 \pm 5$ | 36 |
| $\begin{gathered} d_{x}=d_{y}=9 \mathrm{~cm} \\ d_{z}=11 \mathrm{~cm} \end{gathered}$ | In first plane $4 \times 4=16$ <br> In second plane $4 \times 4=16$ <br> In third plane $/ 4 \times 5 /-1=19$ <br> In fourth plane $4 \times 4=16$ | /Bxtrapolation/ | . . |
| In four planes | 64 | $: 72 \pm 5$ | 27 |
| $\begin{gathered} d_{x}=d_{y}=7.5 \mathrm{~cm} \\ d_{z}=12 \mathrm{~cm} \end{gathered}$ | In each plane $4 \times 4=16$ | /Extrapolation/ |  |
| $d_{y}$ and $d_{y}-d i s$ account wall th | s in plane; $d_{\text {- }}$ - distance between ss, i.e: are dístances between | nes. All dist ns. | take intc |

*/ $d_{y}$ and $d_{y}$ - distances in plane; $d_{z}$ - distance between planes. All distances take into account wall thickness, i.e: are distances between solutions.

Fig．1．Critical masses and volunes of aqueous solutions of $\mathrm{NO}_{2}\left(\mathrm{NO}_{3}\right)_{2}$ （in top right－hand corner）

Cyizinders．
With full $H_{2} O$ reflector：
Without upper reflector：
Rectangular tanks without reflector．

Fig．2．Critical masses and volumes of aqueous solutions of $\mathrm{UO}_{2}\left(\mathrm{NO}_{3}\right)_{2}$ ． （in top right－hand cornor）

Spheres without reflectors

- experiment，curve 1 。
- calculation of geometric parameter，curve 2。

Spheres with water reflector／ourvo 8／：
－experiment－calculation of geometrical parameter with extrapolation
length ．．．．．．
Cylinders without reflector：

Fig．3．fifficiency of cental boron carbide rods and water－filled cadmium tubes as a function of rod radius thecugh absorbent．Reactor without reflector．Diameter of core 400 mm ．

1．Cadmium tube 0.5 m thick，waer－filled．Thickness of steel casing $2-3 \mathrm{~mm}$ ．
2．Boron carbide rods．Thickness of steel casing $2-3 \mathrm{~mm}$ ．
Uranium concentration in the solution $286 \mathrm{~g} / \mathrm{I}$ 。
．．Fig． 4 on．．． Pfficiency of central bonco carbide rods and water－filled cadmiun tubes as a function of rod radius through absorbent。 Reactor without reflector．Dianeter of core 400 mme Jranium concentration in the solution $136 \mathrm{~g} / \mathrm{l}$ ．Gritical volume of reactor without rod 25.61 。

1．Watermilled cadmium tube 0.5 min thick．
2．Boron carbide rud．Thickness of stedl cesing I mmo

Fig：5．Gritical volumes of reactors with ane without an absorbing rod as a function of core dianeter．Peactor with reflector．Diameter of absorbing rod through buron carbide 50 mm ．Thickness of steel casing 4 mm ．

1．Reactor with rod．
2．Reactor without rod．
Curves－uraniun concentration in the solution $286 \mathrm{~g} / \mathrm{I}$ ．
rurves－uraniun concentration in the solution $72 \mathrm{E} / 1$ ．

Fig．6．Efficiency of one and two absorbing rods as a function of their position along the radius of the core．Reactor without reflector， Diameter of core－ 400 ma Urenjur，concentration in the solution $286 \mathrm{~g} / \mathrm{l}$ ．Diameter of absorbing roc through boron carbide 24 mm ． Thickness of steel casing 4 mm ．

1．Efficiency of one rod．
2．Mfficiency of two rods．
3．Double efficiency of one rod：

Fig．7．Fificiency of seven rods．Diamete ${ }^{\prime}$ of ccre 400 mm ．Reactor with side and buttom water reflectors

I．Boron carbide rods 50 ma in diameter．Thickness of steel casing 4 mm ．Jranium concentration $281 \mathrm{~g} / 1$ ．Critical volume without rods 18.071 ．
2．Cadmium rods 46 mm in dianeter，thickness of cadmium 0.5 mm ． Thickness of steel casing 5.5 mm ．Uraniun concentration $457 \mathrm{~g} / \mathrm{I}$ 。 Critical volume without rods 17.561.

Fig. 8. Fificiency of a cluster of boron rods. Diameter of core 40 cm . Reactor with side and bottom water ruflectors. Uranium concentration $281 \mathrm{~g} / \mathrm{L}$.
(at top)

with central rod
without central rod

Fig. 9. Tfficiency of boron and cadmium annular incerts. Cylindrical core 40 mm in diameter. Uraniun concentration $288 \mathrm{~g} / 1$

O - boron insert
$\Delta$ - cadmiun insert
Curves 1 and 2: with side and bottom water reflectors
Curves 3 and 4: without reflectors

Fig. 10. Bfficiency of cadmium annular insorts as a function of the average radius of the annular layer. Cylindrical core 40 cm in diameter with side and botton water reflectors. Uranium concentration $281 \mathrm{~g} / \mathrm{l}$
(at top)
O-annular insert 25 nm thick
$\Delta$ - " " 50 mm "
ロー " " $\quad$ " mm " with polyetlylene instead of water
With an annular insert of average radius 100 inm and thickness of layer 50 mm , 481 of solution were poured in. $\operatorname{sxtrapolation~of~inverse~multiplication~curves~}$ gives a critical volume of 75 l.
(at bottom)
Critical volume without insert - 18.1. 1.

Fig. Il. Interaction of parallelipiped reactors with square base $\quad \leq \quad=300 \mathrm{~mm}$
1 and 2: two and three reactors respeotively.
3: calculation for two reactors.
4: calculation for three reactors.
Uranium concentration in the solution $71 \mathrm{E} / \mathrm{I}$
Arrangement of reactors -

Fig. 12. Interaction of parallelipiped reactors with square base $a=b=300 \mathrm{~mm}$
1, 2, 3 s . three, four and five reactoss raspectively.
48 calculation (first approxiration).
Uranium concentration in the solution $71 \mathrm{~g} / \mathrm{l}$
Arrangement of reactors -

Fig. 13. Interaction of two cylindrical reactors in water.
Diameter of core 30 cm

1. Erperiment
2. Calculation

Uranium concentration in the solution $11.3 \mathrm{~g} / 1$ 。

# - $53-$ <br> (page 402 <br> of original) 

Part III
IUPTHODOLOGICAL QUESTIONS
I. Calculating neutron oross-soctions from the optical model usine a computer
V.E. Kolesov

The development of methods of calculating various cross-sections, and also the carrying out of such calculations, are of great practical as well as theoretical interest. The data obtaincd may be used, for example, to establish systems of multi-group constants for calculating reactors and their biological shielding.

The optical model of the nucleus $[1]$ is widely used to calculate crosssections. It satisfactorily describes in a limited energy range not only the total cross-section $\sigma_{t}$, but also its separate components. Apart from $\sigma_{t}$, it also permits calculation of what is known as the cross-section of optical elastic scattering $\sigma_{n}^{s}$, the cross-section of formation of the compound nucleus (capture cross-scction) $\sigma_{c}$, the transport cross-section $\sigma_{t r}$, and the differential arosssection of optical elastic scattering $\frac{d \sigma_{M 1}}{d \Omega}$. "Optical elastic scattering" here means tho elastic scattering which proceeds without the formation of a compound state。 This cross-section is somotimes called the "cross-section of potential scattering". We follow the text-book [2] for the designation of the various cross-scctions.

The optical model is also widely used for calculating the cross-sections of inelastic scattering $\sigma_{n}$, and radiative capture $\sigma_{\gamma}$, and in calculating the polarization of neutrons. The data obtained by calculations on this modol may also be used to solve other important problems.

Tho various cross-sections and the degree of polarization of the neutrons arc expressed by the coefficients $\eta_{\ell j}$, which determine the ratio between the amplitudes of the outgoing and ingoing spherical waves in the expression for the neutron wave function in the entry channol. For nuclear potentials with a spin-orbital component $\eta_{\ell j}$ depends not only on the orbital moment $\ell$ of the anount of movement of the noutron, but also on the total nomont $j=1 \ell \pm \frac{1}{2} 1$.

To find the amplitude of $\eta_{\ell j}$, it is necessary to solve Schrödinger's equation for the radial part of the wave function. With the forms of optical potential at
prosent in gonoral uso, this oquation is solvod approximately, or various numorical methods are usod which give a final rosult of sufficient accuracy. Computors are normally usod for oarryine out the numerical algorithms.

The present roviov doscribes. britofly tho numerical method of finding the coofficients $\eta_{\ell j}$, and a numbor"or prociramos bascol on this mothod, which mako it possible to calculato the verious noutron cross-scotions within tho framework of the optical modol of the nucleus. Information is also given regarding the tables for cortain cross-sections', coefficionts $\eta$, and penetration factors $T$, calculated according to these programmes with difforent 'ty pos of' potential. : . . . . . . . . . . . . (Acknowledgenents)

Mothod of calculating cross-sections
In the region of space where the nuclear potential $V_{\ell j}(r)$ may be regarded as equal to zero, there exists for Schrödinger's radial equation [3]
an analytical solution in tho form of a linear combination of oylindrical functions. The problom is to find a solution of this cquation in the range of action of nucloar forces. Here the physical boundary condition at zero obtains:

As is known from $[3]$, the cocfificients $\eta_{\ell j}$ are expressed by the logarithmic derivative of equation (1)
at a cortain point $r=H$ wero the potential is already close to zoro with a sufficient degree of accuracy. If cquation (3) is regardod as a second boundary condition, equation (1), together with (2) and (3), forms a boundary value problem in which the logarithmic derivative is an unknown factor.

The solution of this problem by the method of finite differences using the simplest 3 -point differcnce schome loads to a system of high-order linear algebraic levols. The systom being nocessarily solvable, expressions can be obtained for the logarithmic derivative and the recurrent relationship for calculating the doterminant deduced.

For a complex potential, the real and imaginary parts of the logarithmic derjvative are equal
where $h$ is the interval of the finito difference system. The values of $P_{n-1}$, $P_{n-2}, Q_{n-1}$ and $Q_{n-2}$, which have to bo known in order to calculate $f_{\ell^{\prime}}$, are worked out by the recurrent formulas

Here

The form of the initial conditions fox the recurrent relationships depends on where the boundary condition (2) of the problem is placed. When it is set in the form of a logarithmic dorivative of $\pi_{\ell_{j}}$ of the type of (3), at a certain point in the neighbourhood of zero the initial conditions for (4) take the form
where

The function $F(r)$ is completely determined by the form of the potential $V_{Z j}(r)$ 。

No particular restrictions are placed on the nuclear potentialg its form may vary over a wide range. The method permits simple calculation on a computer, and is satisfactorily accurate, with a comparatively low consumption of machine time. The method described here of finding the logarithmic derivative is set out in more detail in reference [4]. The method has considerable seneral practicability, and may be used to calculate not only the cross-sections, but also the bound energy states in the nuclear potential.

The amplitudes of the outgoing waves $\eta_{\ell_{j}}$ are expressed as follows via $f_{\mathbb{L} j}$

The values of $\Delta_{\ell}$, $S_{\ell}$ and $G_{\ell}$ are complotely dotermined by the conditions in the region of space where the potential is equal to zero, and are set using the relationships

The spherical Bessel functions $j_{V}(x)$ entoring into these formulee depend on the variable $x=k H$ and are expressed in their final form by means of trigonometric functions.

Thus, knowing the logarithmic derivative $\mathbb{E}_{j}$, it is possible to calculate, by known formulae, the cross-seotionsfor the interaction of neutrons with the nuclei. For example the expressions for the integral cross-sections $\sigma_{n}^{s} \sigma_{c}$ and $\sigma_{t}$ take the form
where
the so-called penetration factors, which represent the probability of a neutron penetrating the surface of the nucleus. These factors are widely used in calculating the cross-sections of inelastic scattoring and radiative capture of neutrons.

## Characteristics of procrammes

The method described above proved very offective, and was used as the basis of a number of programmes for calculating various noutron cross-sections, employing the optical model of the nucleus. The possibilities of some programmes with potentials of different forms for differont computers are described below.

1. Programmes for the "Strola" computer

Two types of programme are possible for this machine: (a) for potential without spin-orbit interaction $[5]$ and (b) for potential taking the spin-orbit interaction into account [6].
(a) The original varient of the programme [5] was set up for the potential
with spin-orbit interaction not taken into account. The programme permits calculation of $\sigma_{n}^{s}, \sigma_{c}, \sigma_{t}$ and the differential cross-section $\frac{d \sigma_{n}^{s}}{d \Omega}$, in this case expressed as follows via $\eta_{\ell}$ and the Legendre polynomials $P_{\ell}(\mu)$.

Certain alterations were subsequently made to the programme $[7]$ so that the formula could also be used to calculate the transport cross-section $\sigma_{t r}$ :

The progranme was so arranged that after one insertion of the initial information it was possible to calculate the cross-sections for five nuclei with any mass numbers $A$ and any parameters of potential (6) for each $A$. The number of variants in energy and the maximum orbital moment $l_{\max }$ were set, The number of nuclei, and also the number of variants in energy and the number of harmonics for which the calculation is carried out, can be reduced to any figure. Reduction of $\ell_{\text {max }}$ gives in many cases a notable saving of machine time, without detriment to the accuracy of the calculations, To save time, the programme provides for the possibility of not calculating the angular distributions for some, or even for all, energies.

The parameters of potential and the other data and constants necessary for the calculations and for controlling the operation of the computer are inserted into the operative memory of the machine together with the programme, as initial data for the calculation. The final results, printed or on punched cards, are $A, E(H e V)$, the cross-sections $\sigma_{1}^{s}, \sigma_{c}, \sigma_{t}$ and $\sigma_{t r}$ in barns, the values of Ren $\eta_{\mathcal{Q}}$ and the penetration factor $T \ell$ (with signs of the corresponding values of $\operatorname{Im} \eta \ell$ ) for each $l$, and the angular distributions $\sigma_{n}^{s}(\mu)(i n b / s r)$ for $\mu$ in the range from -1 to +1 at intervals of 0.1 . The value of $\frac{\pi^{n}}{k^{2}}$ is also obtained (in units of $10^{-24} \mathrm{~cm}^{2}$ ), which makes it possible to quickly calculate the partial cross-sections $c_{c}(\mathbb{Q})$. Since the penetration factors $T_{l}$ are positive in their physical sense, it is possible, knowing the sign of $I^{\prime} \eta_{\ell}$, to re-establish the imaginary part of the amplitude Im $\ell$ from the known Ren $\ell$ and $T \ell$ using (5).

The required accuracy of calculation can be attained by correct choice of the interval h. Experience shows that it takes an average of about a minute to calculate one variant (one energy with a fixed set of parameters of potential) with an interval of $h=0.1$, which gives the final results an accuracy of the order of $0.5 \%$. This time varies slightly for light and heavy nuclei, and depends on the energy, i.e. on the value of $\ell_{\text {max. }}$.

The programme makes provision for control of the accuracy of the calculations by machine; this is achieved by repeated checks using magnetic tape. If the control totals of two checks do not agree, the proframme provides for a third check. The machine stops if all three totals do not agree.
(b) The programme [6] for the case when the nuclear potential contains a spinorbital component of the type (for $\mathcal{L} \neq 0$ )
where $V(r)$ is set by formula (6), is a modification of the previous programme $[5]$. They therefore both have the same possibilities except that the programme taking into account the spin-orbit interaction does not provide for calculation of the angular distributions and transport cross-sections. The time taken to calculate the cross-sections is roughly doubled in this case. It is also possible to use the programme for calculations with a potential having no spin-orbital component, if $\chi$ is taken as equal to 0 .

## 2. Programmes for the BESM-2 computer

Two programmes will be described. One of then [8] affords the possibility of calculating, as well as the othor oross-sections, those for inelastic scattering and radiative capture of neutrons. The second [9] provides for calculations according to the optical model in the case of both volume and surface absorption of neutrons.
(a) The programme [8] takes the potential (6) corresponding to the case of volume absorption. For a nucleus with mass number A, particular parameters of potential and the other nuclear characteristics necessary for the calculations, the programme permits calculation of the following cross-sections
where $\sigma_{n}^{(m)}$ is the cross-section for inelastic scattering with excitation of the $m^{\text {th }}$ level and $\sigma_{\gamma}^{(\ell)}$ is the partial cross-section for radiative capture for the $\ell^{\text {th }}$ harmonic. Apart from calculating the above cross-section it is also possible to calculate their various combinations. This must be reflected by sotting the appropriate constant in the special sign cell.

The functions of excitation of the separate levels $\sigma_{11}^{\prime}(\mathrm{m})$ are calculated by the Hauser-Feshbach formula $[10]$, and the cross-section $\sigma \gamma$, taking into account the concurrence of elastic and inelastic scattering, by the formula of Margolis [ll]. The theory of these cross-sections assumes that the processes reviewed pass through the stage of a compound nucleus, whose decay does not depend on the method of formation. It is accepted that statistical inspection is valid for a compound nucleus. In the calculations, it is also assumed that the variation of the energy dependence of the neutron penetration factors does not depend on whether the nucleus is in the ground state or in one of its oxcited states. The energy dependence of the radiation widths is taken into account. For the density of the levels, the simplest relationship which follows from the Fermi-ges model is used.

The initial data required for calculating the cross-sections are placed in the special settirg zone on punched tape. The operator sets the parameters of optical potential, energy, spin and symmetry of the levels excited in inelastic scattering, the parameter characterizing density of the levels in the Fermi-gas model, the ratio of the arerage distance between the levels of the compound nucleus to the average radiation vidth, multiplied by $2 \pi$, at an excitation energy equal to the effective energy (taking into account the energy of pairing) of the neutron bond in the compound nucleus, and the effective energy of the bond, together with certain other data and constants for controlling the operation of the machine. The symmetry and spin characteriaing the state of the nucleus are set in combination, the symmetry being set in the form of a sign on the appropriate spin value. The number of levels of the nucleus may be as high as 15. The number of energy variants may be set at any value desired by rising a special constant in the setting zone. The number of harmonics contributing to each different type of cross-section is determined automatically using the conditions
where $\Sigma$ is a positive number, set in the setting zone, determined by the accuracy required in the results.

The final results printed are $A, \mathbb{B}(M e V)$, the cross-sections (in barns), and also the values of Ren $\ell$ and $T \ell$ for different values of $l$ and the constant $\frac{\pi}{k^{2}}$ (in barns)。 The cross-sections $\sigma_{n}^{s}(\mu)$ (in $h / s r$ ) are printed for different $\mu$ values $(-1 \leqslant \mu \leqslant 1)$ at intervals of 0.1 . The signs of the coefficients. Imne are used for the penetration factors $T$. This makes it possible to re-establish from known $T l$ and $R e \eta l$ figures the values of Impl.

The time taken by the machine to calculate one energy variant for a given $A$ depends on the nature of the cross-seotions calculated. Calculating inelastic scattering cross-sections takes longest. Double counting is used as a check that the machine is operating properly. Renewal of the programme in the case of faulty operation is done from a magnetic drum.
(b) The second programme [9] permits calculation for two types of optical potential when spin-orbit interaction is absent: potential of the type (6), and a potential whose real part coincides with (6) and whose imaginary part has the form

The first of these potentials corresponds to the case of volume absorption and the second to that of surface absorption. The machine is set for one case or the other by setting a special constant in the setting zone.

In its characteristics and possibilities the programme is generally similar to that described above for the "Strela" computer [5], but requires three to four times less machine time for calculating a variant.
3. At present programme 12 has been set up, to calculate various crosssections including those for inelastic scattering and radiative capture of neutrons. -The experience gained in using the programmes described above was taken into account in drawing up this programme. This made it possible to introduce a number of modifications vhich considerably improved it. In particular, it became possible to considerably shorten the time taken to calculate one variant, especially when calculating the very labour-consuming cross-sections for inelastic scattering (up to several minutes).

As regards type of potential, the programme permits calculation for the following four cases:
(1) Volume absorption without spin-orbit interaction
(2) Volume absorption taking the spin-orbit interaction into account
(3) Surface absorption without spin-orbit interaction
(4). Surface absorption taking the spin̄-orbit interaction into account. The form of the potentials is Eiven by expressions (6), (7) and (8). From the point of view of possibilities, this programme combines the advantages of both the programmes for the BESII-2.

## Results of tho calculations

The programes described above are at present being used for calculating different types of cross-section, and the data obtained from these calculations are widely employed in the analysis and systematization of experimental data, as well as for other purposes. The programmes have also been used to compile extensive tables of certain cross-sections, the coefficients $\eta$ and the penetration factors $T$ for a wide range of energies and atomic weights, and for potentials of different forms with certain optimum parameters. These tables can be of use for all kinds of rough calculations.

As has already been observed, to calculate the cross-sections and the polarization of neutrons according to the optical model, it is sufficient to hatre only complex amplitudes. However, to calculate $\sigma_{r_{1}}{ }^{\prime}$ and $c_{\gamma}$ only the penetration factors $T$, which are certain combinations of $\eta$, are necessary. For confenience in calculating these cross-sections, the literature often gives data only for $T$. Detailed calculations of $T$ for the case of surface absorption, taking into account the spin-orbit interaction, have been carried out by the authors of paper [ 13$]$, published in 1963 in the form of a report. The calculations cover the energy range from 0.1 MeV to 5 MeV at $\mathrm{A}=100$ and up to 3 MeV at $\mathrm{A}=100$ (sic). Some data on calculating the cocfficients T are also given in the monograph of P.E. Nemirovsky [l]. Howerer, knowledge of $T$ alone is in many cases insufficient for calculations according to the optical model. It is therefore certainly desirable to have deta on the amplitudes $\eta$.

We give here some information about the tables containing data on the cross-sections and the coefficients $\eta$ and $T$. At prosent such tables exist for three types of nuclear potential.

- I. Volume absorption not taking the spin-orbit interaction into account [14]

The tables include the cross-nections $\sigma^{s}{ }_{n}, \sigma_{c} ; \sigma_{t}, \sigma_{t r}$ and the values of $\frac{\pi}{k^{2}}$, $\operatorname{Re} \eta_{\ell}$ and $T_{i}$ (with the sign $\operatorname{Im} \eta_{i}$ ) for different values of $\hat{l}$. As has already been noted, the absolute value of Imny may be found by formula (5) . Some of these results are included as an appendix to the reference book $[2]$ (p.484).

The calculations were carried out by programme [5] for 59 nuclei with mass numbers from $A=7$ to $A=248$. The selection of $A$ values for which the calculations were made corresponcis approximately to an ever rate of change in nucleus size. 15 atrictly fixed energy values $E$ in the range 100 kev to 15 MeV were taken for each rucleus, the range up to 1 MeV being studied in greater detail. . Identical parameters of potential (6) were used for all nuclei and energies. The calculations were carried out for the following sets of these parameters:

The values of and $r_{0}$ are given here and subsequently in units of $10^{-13} \mathrm{~cm}$. The parameter $r_{o}$ is determined by the radius of the nucleus $R$, assuming that $R$ changes according to the law $R=I_{0} A^{I / 3}$.

The parameters used here agree with the data published by many authors who have carried out-calculations according to the optical model.
2. Surface absorption not taking the spin-orbit interaction into account [15]

The calculations were carried out by programme $[9]$ for the same nuclei and. energies as in the above case, with parameters of potentials (6) and (8)

The parameter $b$, like $a$ and $r_{o}$ is given in units of $10^{-13} \mathrm{~cm}$. The tables contain all the data referred to in the previous case, and also the differential cross-sections $\sigma_{n}^{S}(\mu)$ for all the nuclei and energies.
3. Volume absorption taking spin-orbit interaction into account [16]

The calculations were carried out using programme [12]. The same mass numbers $A$ and energies $E$ were used as in the two precedirg cases, with the following set of parameters for potentials (6) and (7)

of the last three are given for different values of $l$ and $j$.
(Bibliography)

## II. Analysis of datia obtained using a fast-neutron single-crystal scintillation spectroneter <br> V. Go Zolotukhin et al.

The fast-neutron single-crystal scintillation speotrometer hes in recent years attained wide use, as a result of its ability to separate proton pulses frorn those caused by electrons. A number of papers [1-5] have discussed the problem of the characteristios of the scintillation detector as a spectrometer line form and deteoting efficiency. Conditions have been discovered under which the simplest approximation of single scattering on protons is applicable, as also are quantitative corrections which the authors consider prevent rost of the error caused by distortions of the right-angle distribution of the energies of the recoil protons owing to multiple scattering and boundary effect. The besic equation
where $P_{3}\left(T_{p}\right)$ is the observed distribution of the total energy of the recoil protons due to neutrons with the spectrum $N\left(F_{n}\right)$, and $K\left(E_{p}, I_{n}\right)$ is the analogous distribution from monochromatic neutrons, may be presented, aftor differentiation in respect of $E_{p}$, in the form
where
$H$ is the thickness of the crystal and $\mathcal{H}_{\mathrm{H}}\left(\mathrm{I}_{\mathrm{n}}\right)$ is the macroscopic cross-section for $n-p$ scattering.

The extent to which the factor at $N\left(\mathbb{N}_{p}\right)$ in the right-hand part of (2) diverges from unity characterizes th: effect of distortions of the right-angle form of the line on account of the rffects mentioned. Disregarding the integral in curly brackets, the correction is reduced to calculating the quantity $\frac{K\left(\mathbb{P}_{p}, \mathbb{B}_{p}\right)}{\mathrm{K}_{\mathrm{H}}\left(\mathrm{E}_{\mathrm{p}}, \mathbb{F}_{p}\right)}$, equal to the proportion in which the height of the plateau decreases or increases when $E_{p}=B_{n}$. This correction was calculated in reference $[3]$, assuming the linearity of the luninescence yield and taking into acount only twofold scattering of the neutron on the protons.

Sinilar calculations of forn of the ine $\mathbb{X}\left(J_{n}\right)$ for a stilbene orystal which we have carried out by the Morte Cario mothod make it possible to assess the arror in the approximation
and to propose matrix methods of solving equation (I) for crystals of considerable size. A detailed description of the method of calculation and of sorie results is given in references [6] to [8].

Fig. I shows the form of the line $\frac{K\left(T_{p}, E_{n}\right)}{\mathrm{K}_{\mathrm{H}}\left(\bar{I}_{p}, \tilde{m}_{n}\right)}$ for a cyindrical Stilbene crystal 30 min height and 30 mm in diameter (neutron enerey $\mathrm{E}_{\mathrm{n}}=1.0 ; 4.15 \mathrm{IfeV}$ ). The presence of a contribution from multiple scattering is shown by a rise in the probability density. It is of basic importance that tris rise, as a result of the considerable non-linearity of the luminescence yiell of Stilbene (varying approrimately as $\mathbb{y}_{\mathrm{p}} \bar{j} / 2$, oosurs not in the range $J_{p}=J_{n}$, as it would with a Jinear relationship between the energy of the recoil proton and the amplitude of the light pulse, but in the ringe $\mathrm{S}_{\mathrm{p}} \simeq 0.75 \mathrm{I}_{\mathrm{n}}$. Furthermore, when $\mathrm{E}_{\mathrm{p}}=\mathrm{E}_{\mathrm{n}}$ there is a reduction in the height os the plateau, so that the value of
is loss than unity. This roduction in height can easily be calculated if we take into account that a neutron if energy $\mathrm{D}_{\mathrm{n}}$ can give recoil protons with a total enerey $E_{n}$, either as a resuly. of first, head-on collision (the probability of which is . . . . . . . ) or as a recult of multiple scattering on protons, causing the appearance of a light pulse corresponding to the energy $E_{n}$ of the proton. As a result of the ron-lineari.ty of the luminescence yield the latter possibility is not realizad, and therefore
where . . . . . . . ... . is the macroscopic cross-section for interaction of the neutrons with carbon nuciei. Formula (3) is confirmed by the results of accurate calculation for crystal sizes at which the boundary eifect is of no great importance.

The valuos of . . . . . . . . . found by numerical differentiation of the histograns are given in Figs. 2 and 3 for different Stilbene crystal sizes and for energies of $E_{n}=1.05$ and 2.0 MeV . Using these curves and formulae (2) and (3) it is possible to calculate for a particular form of the spectrum the errors introduced by multiple scattering.

It should be noted that these exrors are essentially dependent on the form of the spectrum. For a "white" spectrum $\mathbb{N}\left(\pi_{n}\right) / \mathbb{N}\left(\pi_{p}\right)=$ const. $=1$ there is a . notable compensation of errors. Table I gives the results of a calculation by formulae (2) and (3), together with the data of Brook and Anderson, for a orystal $30 \times 30 \mathrm{~mm}$.

- Errors of the differentiation method caused by multiple scattering. \%
Data of [3]
Data of present work

Thus for smoth, slowly changing spectra the errors of the differentiation method caused by multiple scattering clearly lie within the linits of error due to statistics, accuracy of calibration, etc.

It can be shown that the formula
where $R\left(F_{n}\right)$ is the path length of a proton of energy $F_{n}$, is accurate for the boundary effect. Here, too, there is a certain compensation of the error fior $\mathrm{E}_{\mathrm{p}}=\mathbb{T}_{\mathrm{n}}$ 。 For a crystal with $\mathrm{H} \geqslant 30 \mathrm{~mm}$ and $\mathrm{B}_{\mathrm{p}} \leq 14$ NeV the boundary effect may be disregarded.

To sum up the discussion of the accurary of the differentiation method, for slowly changing spectra the systematic errces connected with distortion of the line form are within the limits of a few pur cent. The spectrometry mathod itself can hardly guarantee such ecocuracy, and there are therefore no obstacles to using crystals 20 to 40 mm high.

Fast-changing neutron spectra consti.tute an exceptiong in this case the error of the differentiation method may ve considerable. Here the development of matrix methods of solving equation (i), taking into account the real line form of the spectrometer and also its energy resolution, is desirable.

The work in question makes en accurate allowence for the energy resolution of the detector, and matrices are calculated for analysing spectrograns. The kernel of equation ( 1 ), $K\left(E, E_{n}\right)$, taking energy resolution into account, takes the form
where $V\left(\mathrm{~F}_{\mathrm{p}}\right)$ is the average amplitude of the pulse from a proton of energy $\mathrm{E}_{\mathrm{p}}$, $\varepsilon^{2}\left(E_{p}\right)$ is the standard deviation in the distribution of the pulses from monokinetic protons, and $K_{o}\left(T_{p}, \mathbb{T}_{n}\right)$ is the line form found by the Nonte Carlo method.

The energy dependence of the stanaard deviation, according to reference $[4]$, tikes the form . . . . . . Using the energy dependence of the Iuminescence yield in the form $\bar{V}=k \mathrm{~B}^{\overline{3}} 2$, we obtain a rolationship between $\sigma_{0}^{1}$ and $\sigma_{0}$

$$
\sigma_{0}=3 / 2 \sigma_{0}^{\prime}
$$

The calculations were carried out for throe values of the parameter $\sigma_{0}-0.07$, 0.13 and 0.19. From the line forms found for 55 values of $\Phi_{n}[8]$, the counter detection efficiencies for the above three values of $\sigma_{0}$ were calculated. Fig' 4 gives one example (calculated) of the extent. to which counter detection efficiency is energy-dependent, taking energy resolution into account.

The matrix method used for analysing the spectrogram was the counting efficiencies mothod [9]. In this, the system of linear algebraic equations takes the form
where $B_{i}$ is the energy threshold of the counter. All the units of the quadrature trapezium formula, except the first, coincided with the spacing of energy thresholds. To improve the conditionality of the system of equations $[10]$, the first unit was situated at a point where the effectiveness was in practice zero.

The number of columns in the matrix then became equal to n-1. To give a quadratic matrix, the last row and the corresponding right-hand pert were discarded. As a result of these operations the small diagonal elements of the
quadratic matrix of the $n^{\text {th }}$ order become semi-diagonal elements in the quadratic matrix of the $n-1$ th order, which gives considerably better conditionalitiy of the system of equations.
: Table II gives the direct matrix of the $32 n$ order for $\Delta E=0.5 \mathrm{MeV}$ and $\sigma_{0}=0$. The matrix for any o value different fron zero is obtained by displacing the diagonal elements and adding semi-diagonal olements. The diagonal and semi-diagonal elements for the above values of the constant $\sigma_{0}$ are given in the same table, and can be obtained for intermediate $\sigma_{0}$ values by interpolation. In the same table are given the first diagonal elenents, and also the semidiagonal elements, for a matrix with an interval of $\angle E=1.0$ MeV and the same values of the consuant $\sigma_{0}$.

Table III gives the invorse transposed matrix of second difrerences [9] of the $32 n d$ order for $\Delta P=0.5$ MeV and $\sigma_{0}=0$, and Tables IV and $V$ give the inverse transposed matrices of sacond differences of the 19 th order for $\sigma_{0}=0.07$ and $\sigma_{0}=0.13$. The system of equations for $\sigma_{0}=0.19$ is badly conditioned even in the cuse of a matrix of the 19th order. In this case, the method of regularization [11, 12] must be used; this requires analysis of each spectrogram using a computer.

Fig. 5 gives the results of analysis of the spectrum of fast neutrons from a Po-Be source using matrices corresponding to the above values of the constant $\sigma_{0}$, the regularization method being used in the case of $\sigma_{0}=0.19$. It can be seen from Figg. 6 that by taking into account the resolution of the detector it is possible to show the fine structure of the spectrum of neutrons from a Po-Be source. The resolution of the detector in this case was characterized by the constant $\sigma_{0}=0.13$. Comparison of the spectrum we obtained and that obtained by Medvetsky [13] shows their good agreenent (Fig。6) and similarity of fine structure. On the same figure are given the results of a calculation $[3]$ of part of the energy spectrum of the neutrons corresponding to the formation of a $c^{12}$ nucleus in the ground state. As can be seen, the three peaks at neutron energies of $6.6 \mathrm{MeV}, 7.6 \mathrm{MeV}$ and 9.5 MeV agree vell both with the experimental data obtained using photographic plates and with the theoretical spectrum, obtained if account is taken of the anisotropy of the angular distribution of neutrons formed in the $B e^{9}(\alpha, n) C^{12}$ reaction.

Jhe rosults obtained show the great possibilities of matrix analysis of wpoctra with fairly pour detootor lino forms and also the possibility of taking the onergy rosolution acouratoly into account by direct means, in the olements of an orthogonal matirix. The mothod is alsu applicable to the problem of analysing ganma spectra, measured using dotoctors vith either inorganic or organic aointillators.

```
Fig. l Line form of a Stilbene crystal ( }\textrm{F}=\varnothing=30\mathrm{ ) for neutron
        energies of 1.0 MeV (dotted histogram) and 4.15 MeV
        (continuous histogram).
```


$\mathrm{F}_{\mathrm{r}}=1.05 \mathrm{MeV}$ 。
Fig. 3 Values of ............................... as a function of $E_{n}$ for
$\mathrm{E}_{\mathrm{p}}=2.0 \mathrm{MeV}$ 。
Fig. 4 Counter detection efficiency of a Stilbene crystal ( $30 \times 30$ )
(taking resolution into account) for the threshold $B=7.5 \mathrm{MeV}$.
Resolution parameter $\sigma_{0}=0$ (curve 1), $\sigma_{0}=0.07$ (curve 2),
$\sigma_{0}=0.13$ (curve 3), $\sigma_{0}=0.19$ (curve 4).

Fig． 5 Spectrum of neutrons from a Po－Be source，analysed by the matrix method taking resolution into account．The values of the resolution parameter and the numbering of the curves are the same as for Fig。 4 ．

Fig． 6 Spectra of a $P o-B e$ source，obtained（1）in the present paper， （2）by the photographic plates method（ $\sigma_{0}=0.13$ ）， （3）theoretically［3］．


[^0]:    * The spectra of neutrons in reactors in the energy range above 3 MeV normally differ little from that of fission neutrons.
    ** For plane-parallel geometry.

