International Atomic Energy Agency

INDC(CCP)-147/LJV

INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

Comparative Analysis of Recommended Threshold Reaction Cross-Sections on the Basis of Integral Experiments

K.I. Zolotarev, V.M. Bychkov, A.B. Pashchenko,
V.I. Plyaskin, V.N. Manokhin, L.A. Chernov

June 1980

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

Reproduced by the IAEA in Austria
June 1980
80-2930

INDC(CCP)-147/LJV

Comparative Analysis of Recommended Threshold Reaction Cross-Sections on the Basis of Integral Experiments

K.I. Zolotarev, V.M. Bychkov, A.B. Pashchenko,
V.I. Plyaskin, V.N. Manokhin, L.A. Chernov

June 1980

UDK 539.172.4

COMPARATIVE ANALYSIS OF RECOMMENDED THRESHOLD REACTION CROSS-SECTIONS ON THE BASIS OF INTEGRAL EXPERIMENTS

K.I. Zolotarev, V.M. Bychkov, A.B. Pashchenko,
V.I. Plyaskin, V.N. Manokhin, L.A. Chernov

ABSTRACT

COMPARATIVE ANALYSIS OF RECOMMENDED CROSS-SECTIONS FOR THRESHOLD REACTIONS WITH THE USE OF INTEGRAL EXPERIMENTS. The recommended microscopic cross-sections for the $^{56}Fe(n,p)^{56}Mn$ and $^{58}Ni(n,p)^{58}Co$ reactions from the evaluated data libraries ENDF/B-IV, UKNDL and BOSPOR-78 were analysed. A conclusion about the quality of these data was drawn from comparison of experimental neutron spectra with the spectra restored by means of the measured nuclear reaction rates and cross-sections under consideration. It is recommended that the $^{56}Fe(n,p)^{56}Mn$ cross-section reaction from the ENDF/B-IV or UKNDL library and the $^{58}Ni(n,p)^{58}Co$ cross-section reaction from the libraries BOSPOR-78 or ENDF/B-IV should be used. The evaluated cross-sections of the BOSPOR-78 library are given for 8 nuclei in the energy range from the threshold up to 20 MeV.

Libraries of evaluated microscopic cross-sections obtained in various laboratories are now available. Every group of specialists working on activation data spectrometry uses one of these libraries. At the same time, it is known that the accuracy of derivation of neutron spectra from measured values of nuclear reaction rates is to a considerable extent dependent on the accuracy of the micrscopic cross-sections.

The aim of the present paper was to perform a comparative analysis of recommended microscopic cross-sections for the reactions $^{56}Fe(n,p)^{56}Mn$ and $^{58}Ni(n,p)^{58}Co$ on the basis of three libraries: ENDF/B-IV [1], UKNDL [2] and BOSPOR-78 (the library of evaluated threshold reaction cross-sections of the Nuclear Data Centre, Obninsk), on the basis of one method of deriving neutron spectra from measured reaction rates.

Review of evaluated microscopic cross-sections of nuclear reactions

The best-known libraries of evaluated data on microscopic cross-sections of nuclear reactions are ENDF/B-IV, UKNDL and ZACRSS [3]. The

data files of these libraries were obtained on the basis of available experimental results.

The BOSPOR library was set up in 1978 as a result of a critical analysis of the experimental data based on theoretical models of nuclear reactions.

In establishing the BOSPOR-78 library the authors of the library took the view that the experimental information was in most cases insufficient to obtain recommended curves for threshold reaction excitation functions in the incident neutron energy range from the threshold to 20 MeV. In addition, the measurements of various authors often differ considerably from each other, and these discrepancies are greater than the errors quoted. Calculations based on advanced models of the course of nuclear reactions are therefore needed in evaluating nuclear data. In the first place, such calculations make it possible to exclude obviously erroneous data from the whole set of experimental data, and secondly, the calculation results provide the only possible method of evaluating the reaction cross-sections for those ranges of incident neutron energies and target nucleus mass numbers for which no experimental data are available.

In calculating the excitation functions for the description of nuclear reaction cross-sections over a wide range of incident particle energies the reaction mechanism was divided into three processes: direct, pre-equilibrium and equilibrium, according to the reaction's behaviour in time.

Direct processes (knock-on, pick-up, particle stripping, inelastic scattering with excitation of collective degrees of freedom of the target nucleus) take place in the initial stage of the reaction over a period equal to the nuclear interaction time (about 10^{-22} s). In the pre-equilibrium stage of the reaction the excitation energy brought in by the incident particle is distributed among the nucleons in the nucleus.

In this stage particles with an energy exceeding the binding energy of the corresponding particles in the compound nucleus may be emitted (pre-equilibrium emission). The time required for the establishment of thermodynamic equilibrium in the excited nucleus is usually about 10^{-20} s.

In the equilibrium stage of the reaction the excitation energy of the compound nucleus is distributed over many degrees of freedom. Owing to the large number of states in which the compound nucleus may be, the lifetime of the equilibrium phase is about 10^{-16} s.

Particles emitted in different stages of the reaction have different energy distributions: direct and pre-equilibrium processes lead to considerably harder secondary particle spectra than evaporation of particles from the equilibrium state of the compound nucleus.

The contributions of these processes to the total cross-section of inelastic interaction of an incident particle with a nucleus vary with the change in particle energy. At low energies the reaction takes place largely during the equilibrium state of the compound nucleus. As the energy increases the contribution of direct and pre-equilibrium processes grows. In reactions involving emission of charged particles the contribution of equilibrium processes is slight for heavy nuclei even at low energies ($\lesssim$ 20 MeV) because the Coulomb barrier of the nucleus prevents emission of particles with a soft energy spectrum.

The exciton model of Ref. [4], which was further developed by the authors of Refs [5-8], was used to describe pre-equilibrium emission.

The value taken for the matrix element of two-particle interaction was the same as in Ref. [9], where it was obtained from the analysis of the hard component of neutron inelastic scattering spectra. In the model under consideration direct processes can on average also be taken into account.

The emission of particles from the equilibrium state of the nucleus was described in terms of the statistical theory [10]. The residual-nucleus level density parameters required for the calculation were taken from Refs [11-12], and the inverse-reaction cross-sections were calculated by the KOP program [13] with optical potential parameters from Refs [14-15].

All the accessible experimental information from the international library of numerical data on neutron cross-sections EXFOR and the international index to the literature on microscopic neutron data CINDA was used for the evaluation.

The appendix gives recommended values for the excitation functions of threshold reactions for eight nuclei in the incident neutron energy range from the threshold to 20 MeV (BOSPOR-78 data).

The present paper compares the evaluated cross-sections of the nuclear reactions $^{56}Fe(n,p)^{56}Mn$ and $^{58}Ni(n,p)^{58}Co$ from the data of the libraries ENDF/B-IV, UKNDL and BOSPOR-78 (Figs 1(a) and (b)). Unfortunately, the most recent version of the ZACRSS library was not available to the authors and its data could therefore not be compared.

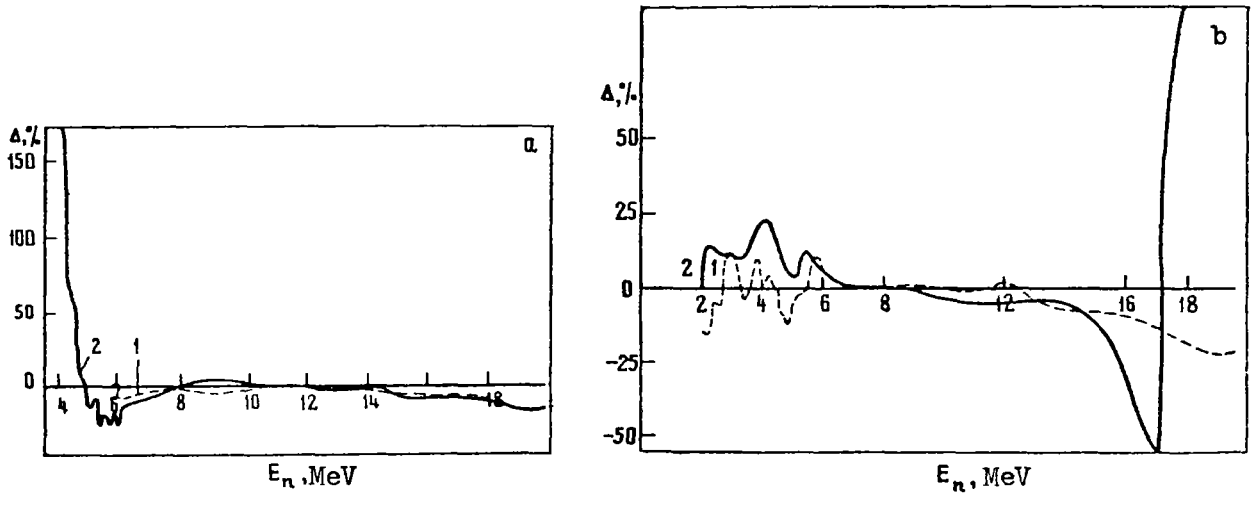

Fig. 1: Relative deviations of the cross-sections for the reactions $^{56}Fe(n,p)^{56}Mn$ (a) and $^{58}Ni(n,p)^{56}Co$ (b) according to ENDF/B-IV (curve 1) and UKNDL (curve 2) data from those of BOSPOR-78.

Method of comparison of the various evaluated files

The principle of the method applied here for the comparative analysis of the various evaluations of microscopic nuclear reaction cross-sections is as follows: using the evaluated microscopic cross-sections as well as the experimental data on reaction rates obtained for a reactor with a known neutron spectrum, a neutron spectrum is derived by means of the GIN program (author K.I. Zolotarev). Initially, a spectrum that is known from experiments is taken as the "true" one. The criterion for the quality of the cross-sections studied is the quantity

$$\delta = \frac{\varphi_б(E_i) - \varphi_э(E_i)}{\varphi_э(E_i)} 100\%,$$

where $\varphi_6(E_i)$ is the neutron flux density at an energy E_i derived from reaction rate data;

$\varphi_э(E_i)$ is the neutron flux density at an energy E_i obtained from experiment.

Experimental data used in the comparative evaluation of cross-sections

The comparative evaluation of data on the cross-sections of the reactions $^{56}Fe(n,p)^{56}Mn$ and $^{58}Ni(n,p)^{58}Co$ was based on the results of differential and integral experiments conducted on a uranium/zirconium hydride critical assembly mounted on the PF-4 rig. The ratio of the nuclear concentrations of hydrogen to ^{235}U in the assembly was about 25.

The authors used data on the energy spectrum of neutrons in the centre of the core of the critical assembly as well as data on the rate of the reactions $^{56}Fe(n,p)^{56}Mn$, $^{58}Ni(n,p)^{58}Co$, $^{24}Mg(n,p)^{24}Na$, $^{27}Al(n,\alpha)^{24}Na$, $^{27}Al(n,p)^{27}Mg$, $^{115}In(n,n')^{115}In^m$ and $^{238}U(n,f)$ at the same point of the core.

The rates of all the reactions except $^{238}U(n,f)$ were measured by the activation method from the induced γ-activity of the isotope samples. The γ-radiation was recorded by a planar GeLi detector with a sensitive volume of about 5 cm^3. The energy resolution of the spectrometer was about 2.7 keV at a γ-quantum energy of 122 keV. Owing to the lack of suitable samples the rate of the $^{238}U(n,f)$ reaction was determined indirectly from the relation $a_f^{238} = \frac{\sigma_f^{238}}{\sigma_f^{235}} a_f^{235}$. The ratio of the fission cross-sections of the isotopes ^{238}U and ^{235}U averaged over the spectrum of the uranium/zirconium hydride critical assembly was measured with the small fission ionization chambers KNT-8 and KNT-5. The rate of ^{235}U fission was measured by the activation method from the 18-keV γ-radiation of ^{140}La.

The total errors in the rates obtained for the reactions $^{56}Fe(n,p)^{56}Mn$ and $^{58}Ni(n,p)^{58}Co$ were 4.6% and 4.7%, respectively. The measurement errors in the rates of the remaining reactions were between 4.6% and 5.5%, and 8.9% for the $^{238}U(n,f)$ reaction.

The differential spectrum of neutrons in the energy range 20 keV–5 MeV is taken from Ref. [16]. The data published in this paper were obtained by direct neutron spectrometry methods. A hydrogen

proportional counter was used for measurements in the energy range from 400 keV downwards, a stilbene counter for the range from 500 keV upwards, and a methane proportional counter for the range 150 keV–2 MeV. The neutron spectrum in the energy range 4–18 MeV was derived by the authors of the present paper from activation data of the detectors: $^{27}Al(n,p)^{27}Mg$, $^{27}Al(n,\alpha)^{24}Na$ and $^{24}Mg(n,p)^{24}Na$. Neutron spectra obtained by different spectrometric methods were normalized with respect to the corresponding overlapping energy ranges. The results of measuring the neutron spectra in the centre of the core of the uranium/zirconium hydride critical assembly in the energy range 0.1–18 MeV are given in Fig. 2.

The mean statistical error in the measurement results obtained by direct neutron spectrometry methods is 2.4% for $E_n \approx 1$ MeV; 5% for $E_n \approx 2$ MeV; 7.1% for $E_n \approx 3$ MeV; 18% for $E_n \approx 4$ MeV and 31% for $E_n \approx 5$ MeV. The error in determining the spectra in the energy range 4–18 MeV (the range of application of activation detectors) does not exceed 15%.

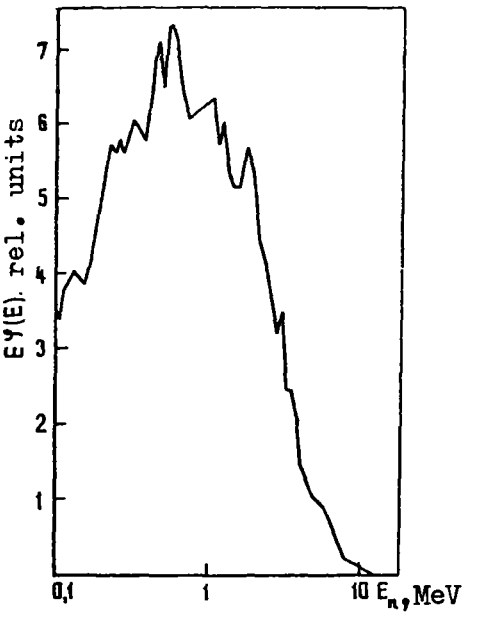

Fig. 2: Energy spectrum of neutrons in the centre of a uranium/zirconium hydride critical assembly.

It should be noted that on the whole the comparison made in Ref. [16] between spectra obtained purely by calculation and experimental spectra shows good agreement. In the energy range 100–600 keV the difference

between the spectra is on average about 10–15%. In the energy range above 1 MeV, which is the most important for the evaluation of the cross-sections for the reactions under consideration, the agreement between the calculated and experimental spectra is considerably better.

The method of deriving the neutron spectrum and the GIN program

The method applied in the present paper to derive the differential neutron spectrum from the measured values of reaction rates is based on the mathematical method SPECTRA, which was first developed by the authors of Ref. [17] and perfected by the authors of Ref. [18].

In this method the unknown differential neutron spectrum $\varphi(E)$ is represented in the form of a continuous piecewise linear function $E\varphi(E)$, the energy dependence of the microscopic cross-sections of the nuclear reactions in the form of a continuous piecewise linear function $\sigma(E)/E$. In this case the system of linear integral Fredholm equations of the first kind may be transformed into the matrix equation

$$\vec{a} = Q\vec{\Phi}, \tag{1}$$

where $\vec{a}$ is a column vector of n elements, which are the measured values of the reaction rates a_i;

$\vec{\Phi}$ is a column vector of m elements, which are the values of the neutron flux density that are sought in given energy points;

Q is a matrix with the dimensions n x m, the elements of which are definite integrals of the reaction cross-sections.

If the rows of matrix Q are assigned to the corresponding elements of the vector $\vec{a}$, and the matrix obtained is designated by C, then Eq. (1) may be rewritten as follows:

$$C\vec{\Phi} = (\vec{1}_n), \tag{2}$$

where $(\vec{1}_n)$ is a column vector of n elements, each of which is equal to unity.

Since a spectrum is usually defined by a number of energy points (m) which is larger than the number of available activation data (n), the solution of Eq. (2) is mathematically indeterminate. To obtain

physically justified results additional information is therefore required. In the present case an initial spectrum $\varphi_0(E)$ is given, and from the spectra satisfying Eq. (2) a spectrum $\varphi(E)$ is determined for which the functionals

$$\int_{E_{min}}^{E_{max}} \left[\frac{\varphi(E)-\varphi_0(E)}{\varphi_0(E)}\right]^2 dE \quad \text{and} \quad \sum_{i=1}^{n}(a_{6i}-a_i)^2 \tag{3}$$

simultaneously take on a minimum value.

Here E_{min} and E_{max} are the lower and upper limits of the energy range in which the spectrum is determined;

a_{bi} and a_i are the calculated and measured reaction rates for the i-th isotope in the unknown spectrum.

To derive an iterative formula on the basis of condition (3) let us write an error function Δ, which characterizes the deviation between the calculated and measured reaction rates in the unknown spectrum, on the one hand, and between the unknown and the initial spectrum, on the other:

$$\Delta_1 = \left[C\Phi_1-(I_n)\right]^T F^2 \left[C\Phi_1-(I_n)\right] + (\Phi_1-\Phi_0)^T G^2(\Phi_1-\Phi_0), \tag{4}$$

where G^2 and F^2 are the diagonal normalization matrices ($\det G \neq 0$, $\det F \neq 0$). It is useful, but not obligatory, to select these matrices such that the elements of matrix G are reciprocals of the corresponding elements of the initial spectrum, and the elements of matrix F are reciprocals of the relative errors in the measurement of the reaction rates.

Minimization of the function Δ_1 with respect to Φ_1 leads to the expression

$$\Phi_1 = G^{-1}\underline{B}[\underline{C}^T F(I_n) + G\Phi_0],$$

where $\underline{B} = (\underline{C}^T\underline{C} + 1)^{-1}$;

$\underline{C} = FCG$.

In analogy to expression (4) we can formulate a new function Δ_2 in which ϕ_1 is assigned instead of ϕ_0 and ϕ_2 instead of ϕ_1. The minimization is performed with respect to the following approximation of the spectrum ϕ_2. If this process is repeated the expression for the unknown spectrum will after k steps take the form

$$\phi_k = G^{-1}\underline{B}\left[\underline{C}^T F(I_n) + G\phi_{k-1}\right]. \qquad (5)$$

Expression (5) is a general formula for an iterative process which continues until the mean-square deviation between the calculated and measured values of the reaction rates attains a given value. The iterative process also ends in the case where the deviation becomes smaller than the corresponding errors in the experimental data on the reaction rates.

The described algorithm including the method of controlling the rate of convergence of the iterative process [18] is incorporated in the GIN program, which is written in the FORTRAN-IV language with reference to the translator of the ES-1030 computer; this program makes it possible to derive the neutron flux density values in 50 energy points. The maximum number of reactions used cannot exceed 30. The reaction cross-section data are entered on magnetic tape, the remaining input data on punched cards. The object module length of the GIN program is about 32K.

Results of the comparison of the cross-sections

The experimental spectrum was assigned in 50 energy points from 0.1 to 18 MeV (see Fig. 2) and used as the initial spectrum. The recommended cross-sections for the reactions $^{56}Fe(n,p)^{56}Mn$ and $^{58}Ni(n,p)^{58}Co$ were analysed on the basis of data from the three libraries.

Two kinds of comparison were made. In the first, only one of the reactions to be analysed was assigned: $^{56}Fe(n,p)^{56}Mn$ or $^{58}Ni(n,p)^{58}Co$, and the deviation of the derived from the true spectrum (Figs 3(a) and (b)) was determined. In the second, the deviation was determined with seven reactions assigned simultaneously: $^{27}Al(n,\alpha)^{24}Na$, $^{27}Al(n,p)^{27}Mg$, $^{24}Mg(n,p)^{24}Na$, $^{115}In(n,n')^{115}In^m$, $^{238}U(n,f)$, $^{56}Fe(n,p)^{56}Mn$ and $^{56}Ni(n,p)^{58}Co$. Data from the ENDF/B-IV, which is the most widely used library, were consistently used for six reactions, except for $^{24}Mg(n,p)^{24}Na$, the cross-section of which was taken from the UKNDL

library. For the seventh reaction the cross-sections were taken alternately from the libraries being compared. The relative deviations of the spectra derived in each of these cases from the experimental spectrum are shown in Fig. 4(a) and (b).

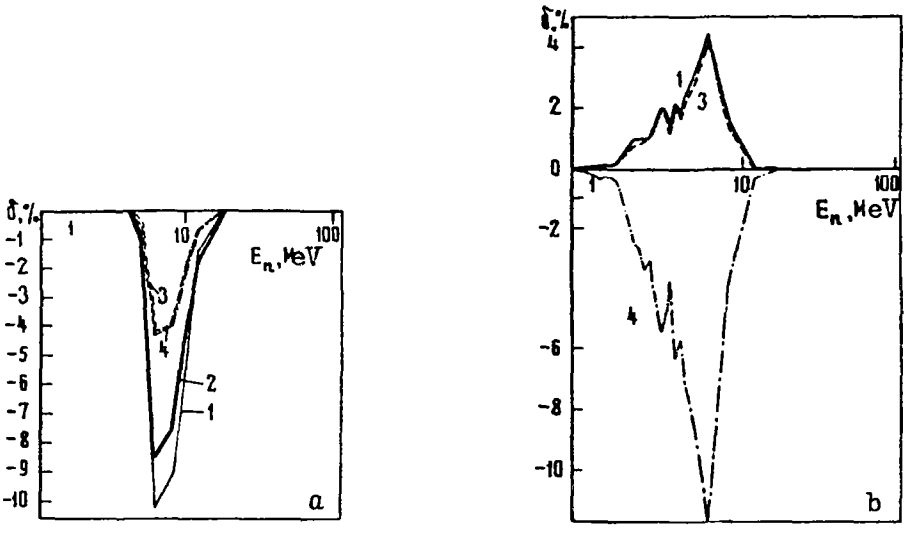

Fig. 3: Relative deviations of spectra derived using only the reactions $^{56}Fe(n,p)^{56}Mn$ (a) and $^{58}Ni(n,p)^{58}Co$ (b) from the experimental spectra.

Data: 1 - BOSPOR-78; 2 - BOSPOR-78 (corrected cross-section); 3 - ENDF/B-IV; 4 - UKNDL.

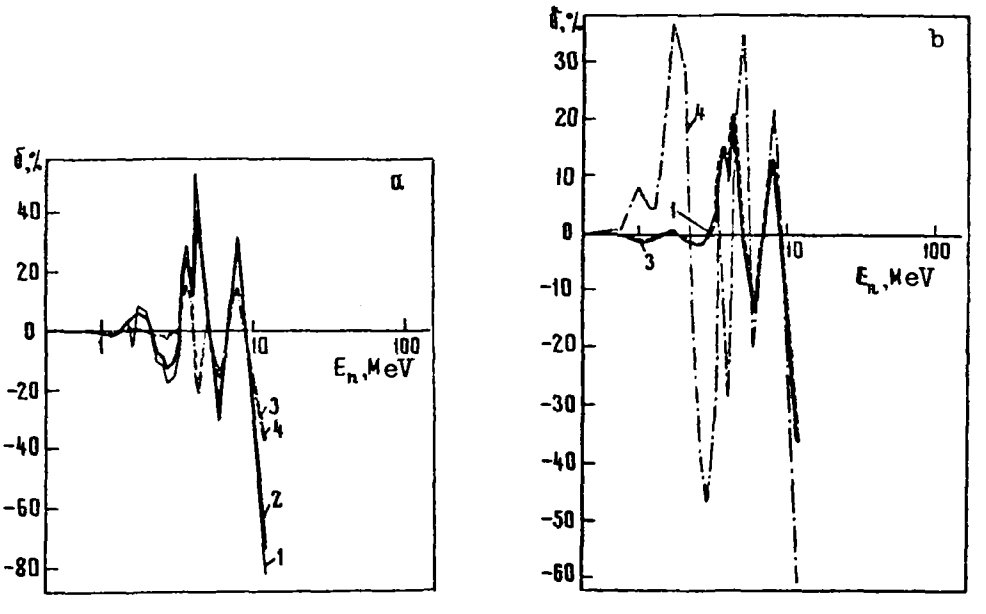

Fig. 4: Relative deviations of spectra derived using a set of 7 reactions from the experimental spectrum. The reactions $^{56}Fe(n,p)^{56}Mn$ (a) and $^{58}Ni(n,p)^{58}Co$ (b) are considered.

Data: 1 - BOSPOR-78; 2 - BOSPOR-78 (corrected cross-section); 3 - ENDF/B-IV; 4 - UKNDL.

Conclusions

The spectra derived by means of data on the reaction $^{58}Ni(n,p)^{58}Co$ from the BOSPOR-78 and ENDF/B-IV libraries gave minimum deviations from the experimentally obtained spectrum. The cross-section data from the UKNDL library showed considerably greater deviations in the derived spectrum for both cases (^{58}Ni in the set and separate) (see Figs 3(b) and 4(b)). In the case where only the reaction $^{58}Ni(n,p)^{58}Co$ (see Fig. 3(b)) was used, the values of the derived spectrum were systematically lower than the experimental data. The maximum deviation was in the region of the reaction rate maximum at 3.5-4.5 MeV. Comparison of the microscopic cross-sections for the reaction $^{58}Ni(n,p)^{58}Co$ shows (see Fig. 1(b)) that the UKNDL data in the energy range 2-8 MeV are systematically higher than the BOSPOR-78 and ENDF/B-IV data. This finding agrees with the results obtained in the present work.

In the activation of the isotope ^{56}Fe the maximum (n,p) reaction rate is in the neutron energy range 6-8 MeV. It can be seen from Fig. 3 that spectra derived with only the reaction $^{56}Fe(n,p)^{56}Mn$ given, using the data sets from the three libraries, are lower than the experimental value of the spectrum. The spectrum calculated from the BOSPOR cross-sections is too low to a greater degree than in the case where cross-section data from the ENDF/B-IV and UKNDL libraries are used. This also agrees with the data presented in Fig. 1(a). On the basis of the preliminary results a correction was made in the micro-cross-sections of the reaction $^{56}Fe(n,p)^{56}Mn$ (BOSPOR-78 data) in the energy range from the threshold to 6 MeV; this leads to some improvement in the description of the spectrum (curve 2 in Figs 3 and 4). However, the data on this reaction from the ENDF/B-IV and UKNDL libraries yield better agreement with the experimental spectrum than the BOSPOR data.

Thus, the results of the comparison make it possible to select and recommend the evaluated cross-sections for the $^{58}Ni(n,p)^{58}Co$ reaction from the ENDF/B-IV or BOSPOR-78 libraries, and the cross-sections for the $^{56}Fe(n,p)^{56}Mn$ reaction from the ENDF/B-IV or UKNDL libraries.

Conclusions may also be drawn from the BOSPOR-78 data about the quality of the cross-sections for the $^{56}Fe(n,p)^{56}Mn$ reaction. In this cross-section the irregularities of the structure in the energy range up to 8 MeV are not taken into account, because the method used for the evaluation yields only a smooth curve of the excitation function. This

energy region accounts for the reaction rate maximum in the spectrum of the uranium/zirconium hydride critical assembly, and therefore it is important to include the resonance structure.

This paper has been concerned with method. In the future, the authors intend to continue the research they have embarked upon, to include well-known standard spectra (e.g. the fission spectra) in the discussion and to analyse a larger number of reactions with a view to arriving at quantitative conclusions concerning the quality of the cross-sections for these reactions over a wider range of energies.

Thus, the proposed method may be used for comparative analysis of various dosimetric files.

REFERENCES

1. M a g u r n o B.A. ENDF/B-IV dosimetry file. Information analysis center report. BNL-NCS-50446, 1975.
2. U.K. Nuclear Evaluated Data. IAEA, ND5113.
3. LAPENAS, A.A., "Izmerenie spektrov nejtronov aktivatsionnym metodom" (Measurement of neutron spectra by the activation method), Zinatne, Riga (1975).
4. G r i f f i n J.J. Phys. Rev. Letters, 1966, v. 17, p. 478.
5. B l a n n M. Ibid., 1968, v. 21, p. 1357.
6. W i l l i a m s F.C. Phys. Letters, 1970, v. 31B, p. 184.
7. C l i n e C.K., B l a n n M. Nucl. Phys., 1971, v. A172, p. 225.
8. B r a g a-M a r c a z z a n C.M., M i l a z z o-C o l l i L. e.a. Phys. Rev., 1972, v. C6, p. 1398.
9. PLYASKIN, V.I., TRYKOVA, V.I., Voprosy atomnoj nauki i tekhniki. Ser. Yadernye konstanty 21 (1976) 62.
10. BLATT, D., WEISSKOPF, V., in "Teoreticheskaya yadernaya fizika" (Theoretical nuclear physics), Izd-vo inostr. lit., Moscow (1954) 288.
11. F a c c h i n i U., S a e t t a-M e n i c h e l l a F. Energia Nucl., 1968, v. 15, p. 54.
12. D i l g W. e.a. Nucl. Phys., 1973, v. A127, p. 269.
13. PASHCHENKO, A.B., in "Yaderno-fizicheskie issledovaniya v SSSR" (Nuclear physics research in the USSR) No. 20, Atomizdat, Moscow (1973) 39.
14. BYCHKOV, V.M., et al., in "Nejtronnaya fizika" (Proc. 3rd All-Union Conference on Neutron Physics, Kiev, 9-13 June 1975), Part 1, Moscow (1976) 160.
15. B e c c h e t t y F.D., G r e e n l e s s G.W. Phys. Rev., 1969, v. 182, p. 1190.
16. BANKRASHKOVA, M.Ya., et al., At. Ehnerg. 44 3 (1978) 260.
17. G r e e r C.L. e.a. A technique for unrolding neutron spectra from activation measurements. Sc-RR-67-746, 1967.
18. TURI, L., FISHER, A., "RFSP: programma dlya opredeleniya spektra nejtronov iz aktivatsionnykh dannykh KFKI-71-22 RPT" (RFSP: a program for the determination of neutron spectra from KFKI-71-22 RPT activation data), Budapest (1971).

APPENDIX

EVALUATED THRESHOLD REACTION CROSS-SECTIONS

E_n, MeV	Reaction cross-section, mb							
	$Cr^{52}(n,p)V^{52}$	$Fe^{54}(n,p)Mn^{54}$	$Fe^{56}(n,p)Mn^{56}$	$Ni^{58}(n,p)Co^{58}$	$Ni^{60}(n,p)Co^{60}$	$Zn^{64}(n,p)Cu^{64}$	$I^{127}(n,2n)I^{126}$	$Tl^{203}(n,2n)Tl^{202}$
0,8	-	-	-	-	-	-	-	-
0,9	-	-	-	-	-	-	-	-
I,0	-	-	-	I,50	-	-	-	-
I,I	-	-	-	2,I8	-	-	-	-
I,2	-	-	-	3,68	-	-	-	-
I,3	-	-	-	5,99	-	0,42	-	-
I,4	-	-	-	9,I2	-	I,28	-	-
I,5	-	-	-	I3,06	-	2,50	-	-
I,6	-	3,0	-	I7,82	-	4,08	-	-
I,7	-	5,8	-	23,39	-	6,02	-	-
I,8	-	8,I	-	29,78	-	8,32	-	-
I,9	-	I4,5	-	36,98	-	I0,98	-	-
2,0	-	2I,0	-	45,00	-	I4,00	-	-
2,I	-	35,0	-	54,93	-	I8,42	-	-
2,2	-	46,0	-	65,44	-	22,96	-	-
2,3	-	58,0	-	76,52	-	27,64	-	-
2,4	-	7I,0	-	88,I6	-	32,44	-	-
2,5	-	80,0	-	I00,38	-	37,38	-	-
2,6	-	94,0	-	II3,I6	-	42,44	-	-
2,7	-	I08,79	-	I26,52	-	47,64	-	-
2,8	-	II9,44	-	I40,44	-	52,96	-	-
2,9	-	I30,5I	-	I54,93	-	58,42	-	-
3,0	-	I42,00	-	I70,00	-	64,00	-	-
3,I	-	I56,03	-	I90,00	-	70,98	-	-
3,2	-	I70,00	-	209,60	-	77,80	-	-
3,3	-	I83,93	-	228,80	-	84,48	-	-
3,4	-	I97,80	-	247,60	-	9I,00	-	-
3,5	-	2II,62	-	266,00	-	97,37	-	-
3,6	-	225,40	-	284,00	-	I03,60	-	-
3,7	-	239,I3	-	30I,60	-	I09,68	-	-
3,8	-	252,80	-	3I8,80	-	II5,60	-	-
3,9	-	266,43	-	335,60	-	I2I,37	-	-
4,0	-	280,00	-	352,00	0,I0	I27,00	-	-

E_n, MeV	Reaction cross-section, mb							
	$Cr^{52}(n,p)V^{52}$	$Fe^{54}(n,p)Mn^{54}$	$Fe^{56}(n,p)Mn^{56}$	$Ni^{58}(n,p)Co^{58}$	$Ni^{60}(n,p)Co^{60}$	$Zn^{64}(n,p)Cu^{64}$	$I^{127}(n,2n)I^{126}$	$Tl^{203}(n,2n)Tl^{202}$
4,I	-	295,82	0,0I	368,72	0,46	I32,39	-	-
4,2	-	3II,08	0,03	384,88	0,95	I37,64	-	-
4,3	-	325,78	0,06	400,48	I,59	I42,76	-	-
4,4	-	339,92	0,09	4I5,52	2,37	I47,76	-	-
4,5	-	353,50	0,I5	430,00	3,29	I52,63	-	-
4,6	-	366,52	0,24	445,92	4,35	I57,36	-	-
4,7	-	378,98	0,38	457,28	5,55	I6I,97	-	-
4,8	0,I2	390,88	0,56	470,08	6,89	I66,44	-	-
4,9	0,40	402,22	0,88	482,32	8,38	I70,79	-	-
5,0	0,75	413,00	I,23	494,00	I0,00	I75,00	-	-
5,I	I,I2	42I,69	I,70	504,00	I2,22	I78,72	-	-
5,2	I,56	430,I6	2,I4	5I3,68	I4,48	I82,40	-	-
5,3	2,07	438,4I	3,28	523,06	I6,78	I86,03	-	-
5,4	2,64	446,64	4,50	532,I2	I9,I2	I89,60	-	-
5,5	3,28	454,25	5,80	540,88	2I,50	I93,I2	-	-
5,6	3,99	46I,84	7,I6	549,32	23,92	I96,60	-	-
5,7	4,77	469,2I	8,50	557,46	26,38	200,03	-	-
5,8	5,6I	476,36	I0,I0	565,28	28,88	203,40	-	-
5,9	6,52	483,29	II,70	572,80	3I,42	206,73	-	-
6,0	7,50	490,00	I4,20	580,00	34,00	2I0,00	-	-
6,I	8,65	496,85	I6,0I	587,2I	36,69	2I3,45	-	-
6,2	9,84	503,40	I7,78	594,04	39,40	2I6,80	-	-
6,3	II,08	509,65	I9,53	600,49	42,I4	220,05	-	-
6,4	I2,36	5I5,60	2I,26	606,56	44,90	223,20	-	-
6,5	I3,69	52I,25	22,95	6I2,25	47,69	226,25	-	-
6,6	I5,06	526,60	24,62	6I7,56	50,50	229,20	-	-
6,7	I6,48	53I,65	26,25	622,49	53,34	232,05	-	-
6,8	I7,94	536,40	27,86	627,04	56,20	234,80	-	-
6,9	I9,45	540,85	29,45	63I,2I	59,09	237,45	-	-
7,0	2I,00	545,00	3I,00	635,00	62,00	240,00	-	-
7,I	22,85	548,I3	32,36	637,38	65,28	242,09	-	-
7,2	24,68	55I,I2	33,72	639,60	68,50	244,I6	-	-
7,3	26,5I	553,97	35,I0	64I,68	7I,68	246,2I	-	-
7,4	28,32	556,68	36,48	643,60	74,80	248,24	-	-
7,5	30,I3	559,25	37,88	645,38	77,88	250,25	-	-

E_n, MeV	Reaction cross-section, mb							
	$Cr^{52}(n,p)V^{52}$	$Fe^{54}(n,p)Mn^{54}$	$Fe^{56}(n,p)Mn^{56}$	$Ni^{58}(n,p)Co^{58}$	$Ni^{60}(n,p)Co^{60}$	$Zn^{64}(n,p)Cu^{64}$	$I^{127}(n,2n)I^{126}$	$Tl^{203}(n,2n)^{202}$
7,6	3I,92	56I,68	39,28	647,00	80,90	252,24	-	-
7,7	33,7I	563,97	40,70	648,48	83,88	254,2I	-	-
7,8	35,48	566,I2	42,I2	649,80	86,80	256,I6	-	-
7,9	37,25	568,I3	43,56	650,98	89,68	258,09	-	-
8,0	39,00	570,00	45,00	652,00	92,50	260,00	-	4,00
8,I	40,68	57I,28	46,59	652,38	95,39	282,07	-	26,95
8,2	42,36	572,52	48,I6	652,72	98,20	264,08	-	52,5I
8,3	44,05	573,72	49,7I	653,02	I00,94	266,03	-	80,68
8,4	45,74	574,88	5I,24	653,28	I03,60	267,92	-	III,45
8,5	47,44	576,00	52,75	653,50	I06,I9	269,75	-	I44,83
8,6	49,I4	577,08	54,24	653,68	I08,70	27I,52	-	I80,8I
8,7	50,85	578,I2	55,7I	653,82	III,I4	273,23	-	2I9,40
8,8	52,56	579,I2	57,I6	653,92	II3,50	274,88	-	260,59
8,9	54,28	580,08	58,59	653,98	II5,79	276,47	-	304,39
9,0	56,00	58I,00	60,00	654,00	II8,00	278,00	-	350,80
9,I	57,86	582,42	6I,2I	654,84	I20,07	279,74	-	4I7,22
9,2	59,70	583,68	62,44	655,44	I22,08	28I,36	-	482,38
9,3	6I,5I	584,78	63,69	655,82	I24,03	282,86	-	546,28
9,4	63,30	585,72	64,96	655,96	I25,92	284,24	-	608,92
9,5	65,06	586,50	66,25	655,88	I27,75	285,50	-	670,29
9,6	66,80	587,I2	67,56	655,56	I29,52	286,64	4,22	730,40
9,7	68,5I	587,58	68,89	655,02	I3I,23	287,66	II,85	789,24
9,8	70,20	587,88	70,24	654,24	I32,88	288,56	2I,46	846,82
9,9	7I,86	588,02	7I,6I	653,24	I34,47	289,34	33,04	903,I4
I0,0	73,50	588,00	73,00	652,00	I36,00	290,00	46,60	958,20
I0,I	75,I4	588,54	74,45	650,85	I37,43	290,90	64,58	I0I5,00
I0,2	76,74	588,76	75,92	649,40	I38,80	29I,60	83,99	I069,88
I0,3	78,32	588,66	77,40	647,65	I40,I3	292,I0	I04,84	II22,82
I0,4	79,86	588,24	78,88	645,60	I4I,40	292,40	I27,I3	II73,82
I0,5	8I,38	587,50	80,38	643,25	I42,63	292,50	I50,85	I222,90
I0,6	82,86	586,44	8I,88	640,60	I43,80	292,40	I76,0I	I270,04
I0,7	84,32	585,06	83,40	637,65	I44,93	292,I0	202,60	I3I5,26
I0,8	85,74	583,36	84,92	634,40	I46,00	29I,60	230,63	I358,54
I0,9	87,I4	58I,34	86,46	630,85	I47,03	290,90	260,I0	I399,88
II,0	88,50	579,00	88,00	627,00	I48,00	290,00	29I,00	I439,30
II,I	89,95	576,25	89,87	622,45	I48,93	288,8I	332,68	I472,82
II,2	9I,34	573,20	9I,68	6I7,68	I49,80	287,44	373,72	I505,29
II,3	92,68	569,85	93,43	6I2,7I	I50,62	285,89	4I4,I2	I536,7I
II,4	93,96	566,20	95,I2	607,52	I5I,40	284,I6	453,88	I567,07

E_n, MeV	Reaction cross-section, mb							
	$Cr^{52}(n,p)V^{52}$	$Fe^{54}(n,p)Mn^{54}$	$Fe^{56}(n,p)Mn^{56}$	$Ni^{58}(n,p)Co^{58}$	$Ni^{60}(n,p)Co^{60}$	$Zn^{64}(n,p)Cu^{64}$	$I^{127}(n,2n)I^{126}$	$Tl^{203}(n,2n)^{202}$
II,5	95,I9	562,25	96,75	602,I3	I52,I3	282,25	493,00	I596,39
II,6	96,36	558,00	98,32	596,52	I52,80	280,I6	53I,48	I624,65
II,7	97,48	553,45	99,83	590,7I	I53,43	277,89	569,32	I65I,87
II,8	98,54	548,60	I0I,28	584,68	I54,00	275,44	606,52	I678,03
II,9	99,55	543,45	I02,67	578,45	I54,53	272,8I	643,08	I703,I4
I2,0	I00,50	538,00	I04,00	572,00	I55,00	270,00	679,00	I727,20
I2,I	I0I,53	530,77	I05,45	564,76	I55,79	266,38	7I6,53	I748,86
22,2	I02,48	523,56	I06,80	557,44	I56,44	262,72	752,92	I769,77
I2,3	I03,34	5I6,39	I08,05	550,04	I56,97	259,02	788,I7	I789,93
I2,4	I04,I2	509,24	I09,20	542,56	I57,36	255,28	822,28	I809,33
I2,5	I04,8I	502,I3	II0,25	535,00	I57,63	25I,50	855,25	I827,99
I2,6	I05,42	495,04	III,20	527,36	I57,76	247,68	887,08	I845,89
I2,7	I05,94	487,99	II2,05	5I9,64	I57,77	243,82	9I7,77	I863,05
I2,8	I06,38	480,96	II2,80	5II,84	I57,64	239,92	947,32	I879,45
I2,9	I06,73	473,97	II3,45	503,96	I57,39	235,98	975,73	I895,I0
I3,0	I07,00	467,00	II4,00	496,00	I57,00	232,00	I003,00	I9I0,00
I3,I	I07,03	460,20	II4,36	487,02	I56,40	227,44	I027,96	I922,8I
I3,2	I07,00	453,40	II4,64	478,I6	I55,68	222,96	I052,04	I935,I7
I3,3	I06,93	446,60	II4,84	469,44	I54,86	2I8,56	I075,24	I947,08
I3,4	I06,80	439,80	II4,96	460,84	I53,92	2I4,24	I097,56	I958,53
I3,5	I06,63	433,00	II5,00	452,38	I52,88	2I0,00	III9,00	I969,53
I3,6	I06,40	426,20	II4,96	444,04	I5I,72	205,84	II39,56	I980,07
I3,7	I06,I3	419,40	II4,84	435,84	I50,46	20I,76	II59,24	I990,I6
I3,8	I05,80	4I2,60	II4,64	427,76	I49,08	197,76	II78,04	I999,79
I3,9	I05,43	405,80	II4,36	4I9,82	I47,60	I93,84	II95,96	2008,97
I4,0	I05,00	399,00	II4,00	4I2,00	I46,00	I90,00	I2I3,00	20I7,70
I4,I	I04,30	392,29	II3,65	404,00	I43,73	I86,24	I227,27	2029,25
I4,2	I03,60	385,56	II3,20	396,20	I4I,48	I82,56	I24I,08	2039,62
I4,3	I02,90	378,8I	II2,65	388,60	I39,24	I78,96	I254,43	2048,8I
I4,4	I02,20	372,04	II2,00	38I,20	I37,02	I75,44	I267,32	2056,82
I4,5	I0I,50	365,25	III,25	374,00	I34,8I	I72,00	I279,75	2063,64
I4,6	I00,80	358,44	II0,40	367,00	I32,62	I68,64	I29I,72	2069,28
I4,7	I00,I0	35I,6I	I09,45	360,20	I30,44	I65,36	I303,23	2073,73

E_n, MeV	Reaction cross-section, mb							
	$Cr^{52}(n,p)V^{52}$	$Fe^{54}(n,p)Mn^{54}$	$Fe^{56}(n,p)Mn^{56}$	$Ni^{58}(n,p)Co^{58}$	$Ni^{60}(n,p)Co^{60}$	$Zn^{64}(n,p)Cu^{64}$	$I^{127}(n,2n)I^{126}$	$Tl^{203}(n,2n)^{202}$
I4,8	99,40	344,76	I08,40	353,60	I28,28	I62,I6	I3I4,28	2077,00
I4,9	98,70	337,89	I07,25	347,20	I26,I3	I59,04	I324,87	2079,09
I5,0	98,00	33I,00	I06,00	34I,00	I24,00	I56,00	I335,00	2080,00
I5,I	97,26	323,46	I04,02	334,9I	I2I,86	I53,40	I347,64	2077,82
I5,2	96,52	3I6,04	I02,08	329,04	II9,74	I50,80	I359,I6	2074,88
I5,3	95,80	308,74	I00,I8	323,39	II7,64	I48,20	I369,56	207I,I8
I5,4	95,08	30I,56	98,32	3I7,96	II5,56	I45,60	I378,84	2066,72
I5,5	94,38	294,50	96,50	3I2,75	I13,50	I43,00	I387,00	206I,50
I5,6	93,68	287,56	94,72	307,76	III,46	I40,40	I394,04	2055,52
I5,7	93,00	280,74	92,98	302,99	I09,44	I37,80	I399,96	2048,78
I5,8	92,32	274,04	9I,28	298,44	I07,44	I35,20	I404,76	204I,28
I5,9	9I,66	267,46	89,62	294,II	I05,46	I32,60	I408,44	2033,02
I6,0	9I,00	26I,00	88,00	290,00	I03,50	I30,00	I4II,00	2024,00
I6,I	90,45	254,I7	86,38	286,20	I0I,36	I27,09	I4I5,46	20I4,85
I6,2	89,88	247,56	84,80	282,60	99,28	I24,24	I4I8,I2	2004,80
I6,3	89,3I	24I,I9	83,28	279,20	97,27	I2I,47	I4I9,00	I993,85
I6,4	88,72	235,04	8I,80	276,00	95,32	II8,76	I4I8,08	I982,00
I6,5	88,I3	229,I3	80,38	273,00	93,44	II6,I3	I4I5,38	I969,25
I6,6	87,52	223,44	79,00	270,20	9I,62	II3,56	I4I0,88	I955,60
I6,7	86,9I	2I7,99	77,68	267,60	89,87	III,07	I404,60	I94I,05
I6,8	86,28	2I2,76	76,40	265,20	88,I8	I08,64	I396,52	I925,60
I6,9	85,65	207,77	75,I8	263,00	86,56	I06,29	I386,66	I909,25
I7,0	85,00	203,00	74,00	26I,00	85,00	I04,00	I375,00	I892,00
I7,I	84,26	I98,78	72,97	259,83	83,58	I02,I0	I356,88	I873,09
I7,2	83,52	I94,72	7I,96	258,72	82,20	I00,20	I338,00	I853,44
I7,3	82,80	I90,82	70,99	257,67	80,88	98,30	I3I8,38	I833,07
I7,4	82,08	I87,08	70,04	256,68	79,60	96,40	I298,00	I8II,96
I7,5	8I,38	I83,50	69,I3	255,75	78,38	94,50	I276,88	I790,I3
I7,6	80,68	I80,08	68,24	254,88	77,20	92,60	I255,00	I767,56
I7,7	80,00	I76,82	67,39	254,07	76,08	90,70	I232,38	I744,27
I7,8	79,32	I73,72	66,56	253,32	75,00	88,80	I209,00	I720,24
I7,9	78,66	I70,78	65,77	252,63	73,98	86,90	II84,87	I695,49
I8,0	78,00	I68,00	65,00	252,00	73,00	85,00	II60,00	I670,00
I8,I	77,36	I65,70	64,40	252,06	72,2I	82,79	II32,35	I639,60
I8,2	76,72	I63,48	63,80	252,04	7I,44	80,64	II04,40	I609,40
I8,3	76,I0	I6I,36	63,20	25I,94	70,69	78,56	I076,I5	I579,40
I8,4	75,48	I59,32	62,60	25I,76	69,90	76,56	I047,60	I549,60
I8,5	74,88	I57,38	62,00	25I,50	69,25	74,63	I0I8,75	I520,00
I8,6	74,28	I55,52	6I,40	25I,I6	68,56	72,76	989,60	I490,60

E_n, MeV	Reaction cross-section, mb							
	$Cr^{52}(n,p)V^{52}$	$Fe^{54}(n,p)Mn^{54}$	$Fe^{56}(n,p)Mn^{56}$	$Ni^{58}(n,p)Co^{58}$	$Ni^{60}(n,p)Co^{60}$	$Zn^{64}(n,p)Cu^{64}$	$I^{127}(n,2n)I^{126}$	$Tl^{203}(n,pn)Tl^{202}$
I8,7	73,70	I53,76	60,80	250,74	67,89	70,97	960,I5	I46I,40
I8,8	73,I2	I52,08	60,20	250,24	67,24	69,24	930,40	I432,40
I8,9	72,56	I50,50	59,60	249,66	66,6I	67,59	900,35	I403,60
I9,0	72,00	I49,00	59,00	249,00	66,00	66,00	870,00	I375,00
I9,I	7I,46	I48,00	58,45	247,77	65,4I	64,7I	838,00	I345,93
I9,2	70,92	I47,00	57,88	246,56	64,84	63,44	806,00	I3I7,20
I9,3	70,40	I46,00	57,3I	245,39	64,29	62,I9	774,00	I288,83
I9,4	69,88	I45,00	56,72	244,24	63,76	60,96	742,00	I260,80
I9,5	69,38	I44,00	56,I3	243,I3	63,25	59,75	7I0,00	I233,I3
I9,6	68,88	I43,00	55,52	242,04	62,76	58,56	678,00	I205,80
I9,7	68,40	I42,00	54,9I	240,99	62,29	57,39	646,00	II78,83
I9,8	67,92	I4I,00	54,28	239,96	6I,84	56,24	6I4,00	II52,20
I9,9	67,46	I40,00	53,65	238,97	6I,4I	55,II	582,00	II25,93
20,0	67,00	I39,00	53,00	238,00	6I,00	54,00	550,00	II00,00