IZVESTIYA AKADEMII NAUK LATVIJSKOJ SSR
(Proceedings of the Academy of Sciences of the Latvian SSR)

1980 No. 4

Seriya Fizicheskikh i Tekhnicheskikh Nauk

PHYSICS OF THE ATOMIC NUCLEUS AND ATOMIC AND MOLECULAR SPECTROSCOPY

UDC 518.5; 539.074.8

Kh.Ya. Bondars, V.A. Kamnev,
A.A. Lapenas, V.S. Troshin

USING THE SAND-II AND MLM METHODS TO RECONSTRUCT FAST NEUTRON SPECTRA

P. Stuchki Latvian State University
Institute of Physics of the Academy of Sciences of the Latvian SSR
Moscow Institute of Physical Engineering

The reconstruction of fast neutron spectra from measured reaction rates may be reduced to the solution of Fredholm's integral equation of the first kind:

$$A_i=\int_0^{E_{\max}} \sigma_i(E)\varphi(E)dE \quad (i=1,2,\dots M), \tag{1}$$

where: A_i is the measured reaction rate of the i-th detector;

$\sigma_i(E)$ is the given energy dependence of the i-th reaction's cross-section;

$\varphi(E)$ is the differential energy dependence of the neutron flux density (unknown function); and

M is the number of detectors.

For a large range of problems it is sufficient to set the upper integration limit E_{max} at ~ 18 MeV.

This problem falls in the category of incorrectly formulated problems, and so additional information is required concerning the unknown function [7], i.e. concerning the differential energy dependence of the neutron flux density $\varphi(E)$.

There are various methods for seeking a solution to the problem as formulated above. One of the best-known methods used in the USSR is the maximum likelihood method (MLM) [5] (or directional difference method (DDM)), whereas SAND-II is commonly used abroad [9, 10].

The purpose of this paper is to compare the MLM [6] and SAND-II [10] methods, taking as an example the processing of measurement data which were obtained in the B-2 beam line at the BR-10 reactor in order to determine the composition of shielding for a fast reactor [4, 8].

In reconstructing the fast neutron spectra we used LIKMET, one of the programs developed for the MLM at the Moscow Institute of Physical Engineering, for use on the ES and BEhSM-6 computers. The LIKMET program can be used with the cross-section from the SAIPS data processing system [1, 2].

Table 1 gives the reaction rates for detectors placed behind steel-graphite shielding of thickness Z = 6.5 cm and Z = 42.5 cm. The energy range of the detectors is also shown (corresponding to a 90% contribution to the reaction rate after a 5% deduction has been made in the low-energy and high-energy parts of the spectrum). Since the spectrum is distorted in a physically unjustifiable way if the cross-section for the $^{35}Cl(n,\alpha)^{32}P$ reaction recommended in Ref. [3] is used, we selected the cross-section for this reaction on the basis of the recommendations made in Ref. [6].

The spectra were reconstructed by means of both methods with a unified energy grouping (620 groups for SAND-II). The efficiency of both methods was checked against a test problem in which the right-hand side corresponded to the reaction rates obtaining with the Watt fission spectrum:

$$\varphi_0(E) = 0{,}484 \exp(-E)\ \mathrm{sh}\sqrt{2E}. \qquad (2)$$

Tables 2 and 3 give the results of neutron spectrum reconstruction /‾4_7 by the MLM and SAND-II methods for shielding thicknesses of $Z = 6.5$ cm and $Z = 42.5$ cm, respectively. The spectra were reconstructed on the basis of three initial approximations. For the first type of approximation, the spectrum was reconstructed by the SAND-II program with detector cross-sections taken from the ZACRSS library /‾1_7; as an initial approximation we took the spectrum from the SAIPS standard spectrum library which gives the best fit with the measured reaction rates. The BGS-1 library was used for spectrum reconstruction by means of the LIKMET program. In both cases the $^{35}Cl(n,\alpha)^{32}P$ reaction cross-section was taken from Ref. /‾6_7 and the $^{31}P(n,p)^{31}Si$ cross-section from the SAND-II library. With the MLM method, the reference spectrum was expressed as $\varphi o(E) = \exp(-\mu E)$, where μ is a factor determined by analysing the high-energy part of the integral spectrum. For the other two types of approximation, the same reference spectra were used, i.e. the 1/E spectrum and the Watt fission neutron spectrum. Apart from the $^{35}Cl(n,\alpha)^{32}P$ and $^{31}P(n,p)^{31}Si$ reactions, the cross-sections were taken from the ZACRSS library.

The following conclusions may be drawn from the results:

(1) Both methods give similar values for the differential spectrum ($<$ 10% difference) using the same cross-section libraries and standard spectra;

(2) For the given set of detectors, the values in the differential neutron spectrum in the 0.5-1.5 MeV region are 15-30% lower with the BGS-1 data than with the ZACRSS data. This is due to the different $^{103}Rh(n,n')^{103}Rh^{m}$ and $^{115}In(n,n')^{115}In^{m}$ reaction cross-section data in the ZACRSS and BGS-1 libraries;

(3) If the initial neutron spectrum is incorrectly selected, the resulting spectrum may be considerably distorted, especially in energy regions where experimental data are scarce. This emerges clearly from the results of spectrum reconstruction (Tables 2 and 3) in the 5.5-12 MeV region, if the 1/E spectrum is used as an initial approximation.

The selection of cut-off criteria in the solution refinement subroutines also has an important influence. If they are taken significantly too high or too low, further distortion of the spectrum results. In the case in question, an integral criterion was selected for both methods, the cut-off being introduced when the resulting spectrum made a given match with the measured detector count rates.

Tables 4 and 5 show the integral energy dependences of fast neutron flux densities with $E_n \geqslant 3.0$ MeV, $E_n \geqslant 2.6$ MeV, $E_n \geqslant 1.0$ MeV, and $E \geqslant 0.5$ MeV. The calculations are based on the reconstructed differential energy dependences of the neutron flux density. As shown in the tables, the spectra reconstructed by each method from different input data do not vary by more than 20%.

The calculations thus show that there is satisfactory agreement between the MLM and SAND-II reconstruction programs, and so they can be recommended for processing the results from activation measurements.

TABLE 1

Detector Reaction Rates and Energy Ranges Corresponding to a 90% Contribution to the Reaction Rate

No.	Detector	Z = 6.5 cm		Z = 42.5 cm	
		A_i	Energy Range, MeV	A_i	Energy Range, MeV
1	$^{103}Rh(n, n')^{103m}Rh$	$6{,}10\cdot10^{-15}$	0,38—2,4	$1{,}33\cdot10^{-16}$	0,20—1,9
2	$^{115}In(n, n')^{115m}In$	$9{,}10\cdot10^{-16}$	0,72—3,5	$1{,}45\cdot10^{-17}$	0,69—3,7
3	$^{232}Th(n, f)$	$1{,}60\cdot10^{-16}$	1,2—5,5	$2{,}00\cdot10^{-18}$	1,2—7,8
4	$^{31}P(n, p)^{31}Si$	$3{,}50\cdot10^{-17}$	1,8—7,0	$4{,}90\cdot10^{-19}$	1,9—8,8
5	$^{32}S(n, p)^{32}P$	$6{,}80\cdot10^{-17}$	2,0—7,5	$9{,}60\cdot10^{-19}$	2,1—9,3
6	$^{35}Cl(n, \alpha)^{32}P$	$2{,}50\cdot10^{-17}$	3,1—8,7	$4{,}90\cdot10^{-19}$	3,4—10,0
7	$^{27}Al(n, p)^{27}Mg$	$3{,}60\cdot10^{-18}$	3,5—9,8	$9{,}40\cdot10^{-20}$	3,9—10,7
8	$^{56}Fe(n, p)^{56}Mn$	$1{,}10\cdot10^{-18}$	5,4—11,6	$3{,}80\cdot10^{-20}$	5,7—12,1
9	$^{24}Mg(n, p)^{24}Na$	$1{,}60\cdot10^{-18}$	6,6—11,9	$6{,}00\cdot10^{-20}$	6,7—12,2
10	$^{27}Al(n, \alpha)^{24}Na$	$8{,}25\cdot10^{-19}$	6,6—12,2	$3{,}30\cdot10^{-20}$	6,8—12,5

TABLE 2

Differential energy dependence of the neutron flux density $[n/cm^2\cdot s\cdot MeV]$ behind shielding Z = 6.5 cm thick

E_n, MeV	SAND-II (sp. 58)	MLM $e^{-\mu E}$	SAND-II 1/E	MLM 1/E	SAND-II WATT	MLM WATT
0,5	$2{,}134\cdot10^{10}$	$1{,}23\cdot10^{10}$	$1{,}723\cdot10^{10}$	$1{,}67\cdot10^{10}$	$1{,}493\cdot10^{10}$	$1{,}45\cdot10^{10}$
0,6	$1{,}729\cdot10^{10}$	$1{,}30\cdot10^{10}$	$1{,}523\cdot10^{10}$	$1{,}49\cdot10^{10}$	$1{,}474\cdot10^{10}$	$1{,}45\cdot10^{10}$
0,7	$1{,}485\cdot10^{10}$	$1{,}31\cdot10^{10}$	$1{,}419\cdot10^{10}$	$1{,}38\cdot10^{10}$	$1{,}413\cdot10^{10}$	$1{,}41\cdot10^{10}$
0,8	$1{,}282\cdot10^{10}$	$1{,}33\cdot10^{10}$	$1{,}302\cdot10^{10}$	$1{,}28\cdot10^{10}$	$1{,}336\cdot10^{10}$	$1{,}36\cdot10^{10}$
0,9	$1{,}082\cdot10^{10}$	$1{,}29\cdot10^{10}$	$1{,}136\cdot10^{10}$	$1{,}16\cdot10^{10}$	$1{,}251\cdot10^{10}$	$1{,}28\cdot10^{10}$
1,0	$9{,}829\cdot10^{9}$	$1{,}18\cdot10^{10}$	$1{,}021\cdot10^{10}$	$1{,}05\cdot10^{10}$	$1{,}103\cdot10^{10}$	$1{,}14\cdot10^{10}$
1,2	$6{,}581\cdot10^{9}$	$6{,}66\cdot10^{9}$	$6{,}596\cdot10^{9}$	$6{,}66\cdot10^{9}$	$6{,}876\cdot10^{9}$	$6{,}92\cdot10^{9}$
1,4	$2{,}699\cdot10^{9}$	$2{,}33\cdot10^{9}$	$2{,}760\cdot10^{9}$	$2{,}90\cdot10^{9}$	$2{,}858\cdot10^{9}$	$2{,}84\cdot10^{9}$
1,6	$1{,}508\cdot10^{9}$	$1{,}29\cdot10^{9}$	$1{,}519\cdot10^{9}$	$1{,}49\cdot10^{9}$	$1{,}487\cdot10^{9}$	$1{,}47\cdot10^{9}$
1,8	$1{,}074\cdot10^{9}$	$9{,}17\cdot10^{8}$	$1{,}002\cdot10^{9}$	$9{,}82\cdot10^{8}$	$1{,}002\cdot10^{9}$	$9{,}87\cdot10^{8}$
2,0	$7{,}239\cdot10^{8}$	$6{,}04\cdot10^{8}$	$6{,}347\cdot10^{8}$	$6{,}02\cdot10^{8}$	$6{,}515\cdot10^{8}$	$6{,}13\cdot10^{8}$
2,5	$2{,}600\cdot10^{8}$	$2{,}49\cdot10^{8}$	$2{,}470\cdot10^{8}$	$2{,}29\cdot10^{8}$	$2{,}525\cdot10^{8}$	$2{,}33\cdot10^{8}$
3,0	$8{,}521\cdot10^{7}$	$1{,}34\cdot10^{8}$	$1{,}283\cdot10^{8}$	$1{,}32\cdot10^{8}$	$1{,}321\cdot10^{8}$	$1{,}33\cdot10^{8}$
3,5	$7{,}457\cdot10^{7}$	$8{,}83\cdot10^{7}$	$8{,}775\cdot10^{7}$	$9{,}04\cdot10^{7}$	$8{,}706\cdot10^{7}$	$8{,}86\cdot10^{7}$
4,0	$6{,}361\cdot10^{7}$	$6{,}36\cdot10^{7}$	$6{,}579\cdot10^{7}$	$7{,}10\cdot10^{7}$	$6{,}076\cdot10^{7}$	$6{,}34\cdot10^{7}$
4,5	$4{,}588\cdot10^{7}$	$4{,}09\cdot10^{7}$	$4{,}661\cdot10^{7}$	$5{,}17\cdot10^{7}$	$4{,}013\cdot10^{7}$	$4{,}20\cdot10^{7}$
5,0	$3{,}529\cdot10^{7}$	$3{,}00\cdot10^{7}$	$3{,}607\cdot10^{7}$	$3{,}71\cdot10^{7}$	$3{,}016\cdot10^{7}$	$3{,}06\cdot10^{7}$
5,5	$2{,}255\cdot10^{7}$	$2{,}07\cdot10^{7}$	$2{,}429\cdot10^{7}$	$2{,}46\cdot10^{7}$	$2{,}001\cdot10^{7}$	$2{,}03\cdot10^{7}$
6,0	$1{,}578\cdot10^{7}$	$1{,}51\cdot10^{7}$	$1{,}526\cdot10^{7}$	$1{,}44\cdot10^{7}$	$1{,}510\cdot10^{7}$	$1{,}51\cdot10^{7}$
6,5	$1{,}145\cdot10^{7}$	$1{,}16\cdot10^{7}$	$9{,}398\cdot10^{6}$	$7{,}09\cdot10^{6}$	$1{,}210\cdot10^{7}$	$1{,}20\cdot10^{7}$
7,0	$8{,}495\cdot10^{6}$	$8{,}62\cdot10^{6}$	$5{,}641\cdot10^{6}$	$4{,}40\cdot10^{6}$	$9{,}123\cdot10^{6}$	$9{,}01\cdot10^{6}$
7,5	$6{,}333\cdot10^{6}$	$6{,}35\cdot10^{6}$	$3{,}728\cdot10^{6}$	$2{,}97\cdot10^{6}$	$6{,}756\cdot10^{6}$	$6{,}69\cdot10^{6}$
8,0	$4{,}512\cdot10^{6}$	$4{,}56\cdot10^{6}$	$2{,}547\cdot10^{6}$	$2{,}01\cdot10^{6}$	$4{,}816\cdot10^{6}$	$4{,}77\cdot10^{6}$
8,5	$3{,}333\cdot10^{6}$	$3{,}33\cdot10^{6}$	$1{,}904\cdot10^{6}$	$1{,}65\cdot10^{6}$	$3{,}452\cdot10^{6}$	$3{,}43\cdot10^{6}$
9,0	$2{,}434\cdot10^{6}$	$2{,}39\cdot10^{6}$	$1{,}630\cdot10^{6}$	$1{,}39\cdot10^{6}$	$2{,}445\cdot10^{6}$	$2{,}44\cdot10^{6}$
9,5	$1{,}765\cdot10^{6}$	$1{,}69\cdot10^{6}$	$1{,}379\cdot10^{6}$	$1{,}22\cdot10^{6}$	$1{,}719\cdot10^{6}$	$1{,}72\cdot10^{6}$
10,0	$1{,}235\cdot10^{6}$	$1{,}19\cdot10^{6}$	$1{,}121\cdot10^{6}$	$1{,}05\cdot10^{6}$	$1{,}178\cdot10^{6}$	$1{,}18\cdot10^{6}$
10,5	$8{,}606\cdot10^{5}$	$8{,}29\cdot10^{5}$	$9{,}147\cdot10^{5}$	$9{,}24\cdot10^{5}$	$8{,}019\cdot10^{5}$	$8{,}05\cdot10^{5}$
11,0	$6{,}085\cdot10^{5}$	$5{,}83\cdot10^{5}$	$8{,}020\cdot10^{5}$	$8{,}42\cdot10^{5}$	$5{,}487\cdot10^{5}$	$5{,}52\cdot10^{5}$
11,5	$4{,}145\cdot10^{5}$	$4{,}06\cdot10^{5}$	$6{,}770\cdot10^{5}$	$7{,}56\cdot10^{5}$	$3{,}660\cdot10^{5}$	$3{,}68\cdot10^{5}$
12,0	$2{,}859\cdot10^{5}$	$2{,}82\cdot10^{5}$	$5{,}868\cdot10^{5}$	$6{,}93\cdot10^{5}$	$2{,}456\cdot10^{5}$	$2{,}47\cdot10^{5}$

TABLE 3

Differential energy dependence of neutron flux density
[n/cm^2·s·MeV] behind shielding Z= 42.5 cm thick

E_n, MeV	SAND-II (sp. 52)	MLM $e^{-\mu E}$	SAND-II 1/E	MLM 1/E	SAND-II WATT	MLM WATT
0,5	4,732·10^8	3,73·10^8	5,214·10^8	5,17·10^8	4,933·10^8	4,98·10^8
0,6	4,138·10^8	3,75·10^8	4,383·10^8	4,37·10^8	4,488·10^8	4,58·10^8
0,7	3,591·10^8	3,67·10^8	3,817·10^8	3,76·10^8	3,903·10^8	4,07·10^8
0,8	3,054·10^8	3,58·10^8	3,276·10^8	3,24·10^8	3,367·10^8	3,52·10^8
0,9	2,410·10^8	3,11·10^8	2,700·10^8	2,78·10^8	2,940·10^8	3,08·10^8
1,0	2,102·10^8	2,50·10^8	2,190·10^8	2,24·10^8	2,300·10^8	2,42·10^8
1,2	1,073·10^8	9,71·10^7	1,079·10^8	1,05·10^8	1,106·10^8	1,06·10^8
1,4	3,449·10^7	2,46·10^7	3,165·10^7	3,22·10^7	3,334·10^7	3,13·10^7
1,6	1,630·10^7	1,29·10^7	1,522·10^7	1,50·10^7	1,537·10^7	1,48·10^7
1,8	1,028·10^7	9,15·10^6	9,629·10^6	9,66·10^6	9,955·10^6	9,68·10^6
2,0	6,285·10^6	5,92·10^6	6,096·10^6	5,92·10^6	6,461·10^6	5,93·10^6
2,5	2,468·10^6	2,44·10^6	2,624·10^6	2,46·10^6	2,704·10^6	2,41·10^6
3,0	1,296·10^6	1,38·10^6	1,345·10^6	1,42·10^6	1,373·10^6	1,36·10^6
3,5	9,749·10^5	1,06·10^6	1,057·10^6	1,10·10^6	9,978·10^5	1,02·10^6
4,0	7,299·10^5	7,63·10^5	8,202·10^5	8,80·10^5	7,001·10^5	7,38·10^5
4,5	6,016·10^5	6,13·10^5	6,917·10^5	7,53·10^5	5,360·10^5	5,75·10^6
5,0	5,526·10^5	5,17·10^5	6,552·10^5	6,61·10^5	4,813·10^5	5,04·10^5
5,5	4,502·10^5	4,13·10^5	5,256·10^5	5,19·10^5	3,862·10^5	4,02·10^5
6,0	3,587·10^5	3,45·10^5	3,729·10^5	3,62·10^5	3,472·10^5	3,51·10^5
6,5	2,946·10^5	3,20·10^5	2,557·10^5	2,17·10^5	3,428·10^5	3,37·10^5
7,0	2,462·10^5	2,64·10^5	1,721·10^5	1,51·10^5	2,962·10^5	2,91·10^5
7,5	2,055·10^5	2,14·10^5	1,244·10^5	1,10·10^5	2,420·10^5	2,38·10^5
8,0	1,661·10^5	1,68·10^5	9,197·10^4	7,71·10^4	1,885·10^5	1,86·10^6
8,5	1,404·10^5	1,31·10^5	7,269·10^4	6,50·10^4	1,405·10^5	1,40·10^5
9,0	1,133·10^6	9,86·10^4	6,449·10^4	5,61·10^4	1,023·10^5	1,02·10^5
9,5	8,229·10^4	7,31·10^4	5,587·10^4	4,97·10^4	7,329·10^4	7,38·10^4
10,0	5,775·10^4	5,34·10^4	4,636·10^4	4,27·10^4	5,130·10^4	5,19·10^4
10,5	4,043·10^4	3,89·10^4	3,849·10^4	3,77·10^4	3,547·10^4	3,60·10^4
11,0	2,873·10^4	2,85·10^4	3,431·10^4	3,46·10^4	2,452·10^4	2,50·10^4
11,5	1,969·10^4	2,06·10^4	2,947·10^4	3,08·10^4	1,657·10^4	1,69·10^4
12,0	1,368·10^4	1,49·10^4	2,598·10^4	2,82·10^4	1,122·10^4	1,15·10^4

TABLE 4

Integral energy dependence of neutron flux density
[n/cm^2·s] behind shielding Z = 6.5 cm thick

	SAND-II (sp. 58)	MLM $e^{-\mu E}$	SAND-II 1/E	MLM 1/E	SAND-II WATT	MLM WATT
$\Phi_{E\geqslant 3,0}$ MeV	1,741·10^8	1,820·10^8	1,932·10^8	1,924·10^8	1,868·10^8	1,830·10^8
$\Phi_{E\geqslant 2,6}$ MeV	2,364·10^8	2,496·10^8	2,664·10^8	2,593·10^8	2,611·10^6	2,508·10^8
$\Phi_{E\geqslant 1,0}$ MeV	4,398·10^9	3,968·10^9	4,431·10^9	3,953·10^9	4,615·10^9	4,079·10^9
$\Phi_{E\geqslant 0,5}$ MeV	1,171·10^{10}	1,039·10^{10}	1,129·10^{10}	1,061·10^9	1,148·10^{10}	1,088·10^{10}

TABLE 5

Integral energy dependence of neutron flux density $[n/cm^2 \cdot s]$ behind shielding Z = 42.5 cm thick

	SAND-II (sp. 52)	MLM $e^{-\mu E}$	SAND-II 1/E	MLM 1/E	SAND-II WATT	MLM WATT·
$\Phi_{E>3,0}$ MeV	$2,923 \cdot 10^6$	$2,910 \cdot 10^6$	$3,067 \cdot 10^6$	$3,070 \cdot 10^6$	$2,895 \cdot 10^6$	$2,882 \cdot 10^6$
$\Phi_{E>2,5}$ MeV	$3,641 \cdot 10^6$	$3,611 \cdot 10^6$	$3,845 \cdot 10^6$	$3,789 \cdot 10^6$	$3,683 \cdot 10^6$	$3,577 \cdot 10^6$
$\Phi_{E>1,0}$ MeV	$7,091 \cdot 10^7$	$6,056 \cdot 10^7$	$7,129 \cdot 10^7$	$5,989 \cdot 10^7$	$7,375 \cdot 10^7$	$6,116 \cdot 10^7$
$\Phi_{E>0,5}$ MeV	$2,427 \cdot 10^8$	$2,332 \cdot 10^8$	$2,548 \cdot 10^8$	$2,378 \cdot 10^8$	$2,610 \cdot 10^8$	$2,504 \cdot 10^8$

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