International Atomic Energy Agency

INDC(CCP)-360
Distr.: G

INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

EVALUATION OF THE $^{46}Ti(n,2n)^{45}Ti$ AND $^{54}Fe(n,2n)^{53m+g}Fe$ REACTION CROSS SECTIONS FOR NEUTRON DOSIMETRY IN FUSION FACILITIES

A paper presented at the International Workshop on Nuclear Data
for Fusion Reactor Technology
Del Mar, California, USA, 3 to 6 May 1993

S.A. Badikov+, A.V. Ignatyuk+, A.B. Pashchenko++, K.I. Zolotarev+

+ Institute of Physics and Power Engineering, Obninsk, Russia
++ International Atomic Energy Agency, Vienna, Austria

November 1993

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

INDC(CCP)-360
Distr.: G

EVALUATION OF THE $^{46}Ti(n,2n)^{45}Ti$ AND $^{54}Fe(n,2n)^{53m+g}Fe$ REACTION CROSS SECTIONS FOR NEUTRON DOSIMETRY IN FUSION FACILITIES

A paper presented at the International Workshop on Nuclear Data
for Fusion Reactor Technology
Del Mar, California, USA, 3 to 6 May 1993

S.A. Badikov+, A.V. Ignatyuk+, A.B. Pashchenko++, K.I. Zolotarev+

+ Institute of Physics and Power Engineering, Obninsk, Russia
++ International Atomic Energy Agency, Vienna, Austria

November 1993

ABSTRACT

The reaction cross-sections of $^{46}Ti(n,2n)^{45}Ti$ and $^{54}Fe(n,2n)^{53m+g}Fe$, which are important for fusion reactor neutron dosimetry, were evaluated using a generalized least squares method. The experimental cross-section data of all measurements performed up to January 1993, were critically reviewed. The evaluated cross-section data are presented in analytical form and in ENDF-6 format, including covariance data.

Reproduced by the IAEA in Austria
November 1993

93-04753

INTRODUCTION

The development of activation detectors having selective sensitivity to neutrons in energy range 13.5-15 MeV is one of the important problems of neutron metrology on fusion facilities. Analysis of reaction cross-sections with high energy threshold indicates the possibility of development of such detectors on the basis of the $^{46}Ti(n,2n)^{45}Ti$ and $^{54}Fe(n,2n)^{53m+g}Fe$ reactions. The energy threshold of enumerated reactions equal to 13.48 MeV and 13.63 MeV respectively.

The production technology of highpurity materials on the basis of metallic titanium and iron for various concentrations of target isotopes is well-developed. So the production of activation detectors with numbers of nuclei of the isotopes ^{46}Ti and ^{54}Fe known within 0.5 ÷ 1% (2σ) doesn't meet difficulties [1].

The uncertainties in decay data for radionuclides ^{45}Ti, ^{53g}Fe, ^{53m}Fe don't exceed 1% (1σ) except for quantum yields of some gamma-lines.

Nowadays the problem of the use of activation detectors on the basis of $^{46}Ti(n,2n)^{45}Ti$ and $^{54}Fe(n,2n)^{53m+g}Fe$ is connected first of all with lack of reliable reaction cross-section evaluation data. In International Reactor Dosimetry File [2] and National Japanese and Chinese Dosimetry Files [3,4] cross-section data for considered reactions are absent. The BOSPOR-86 [6], JENDL-3 [7], REAC-ECN-5 [8] include the evaluated cross-sections for two reactions of interest while ENDF/B-6 library [5] contains $^{54}Fe(n,2n)^{53m+g}Fe$ reaction cross-section evaluation only. All the enumerated evaluations have essential drawback which doesn't permit to use them in neutron dosimetry. These evaluations don't include the covariation matrix of cross-section uncertainties (File 33). Besides that the evaluations from different libraries are inconsistent with each other in some energy ranges. So there is a necessity in new evaluation (which includes covariance information) of the $^{46}Ti(n,2n)^{45}Ti$ and $^{54}Fe(n,2n)^{53m+g}Fe$ reaction cross-sections. It should be noted that the $^{54}Fe(n,2n)^{53m+g}Fe$ reaction cross-section evaluation is important not only for the use in neutron dosimetry. This evaluation is necessary also for

TABLE 1. SUMMARY OF EXPERIMENTS FOR THE REACTION Ti46(n,2n)Ti45

ENERGY-RANGE [MeV]		NR. OF DATA POINTS	METHOD OF MEASUREMENT	MONITOR		REFERENCES		No
14.80	14.80	1	Act, Beta	Cu63(n,2n)Cu62	norm at 14.10 MeV	Poularikas+	59	[10]
14.40	14.40	1	Act, Two NaI(Tl) ,Ann.Gammas Coinc.	Cu63(n,2n)Cu62		Rayburn	61	[11]
13.40	14.93	6	Act, B+ (Ti45),B- (Na24), Prop.count	T(d,n)He4 assoc.pt. and Al27(n,a)Na24		Prestwood+	61	[12]
16.50	19.76	3	Act,B+,Prop.count,Fiss cout,R.Chem.	U238(n,f)FP		Prestwood+	61	[12]
14.13	14.13	1	Act, NaI(Tl) ,Ann.Gammas	T(d,n)He4 assoc.pt.		Cevolani+	62	[13]
14.70	14.70	1	Act, NaI(Tl), Gamma	Al27(n,a)Na24		Strain +	65	[14]
14.10	19.60	7	Act, Two NaI(Tl) ,Ann.Gammas Coinc.	1-H-1(n,n)1-H-1		Bormann+	65	[15]
14.60	14.60	1	Act, NaI(Tl), Ann.Gammas	Cu63(n,2n)Cu62		Csikai	65	[16]
13.60	14.80	2	Act,NaI,Ann.Gammas, 4P B-G counter	Al27(n,a)Na24		Pai	66	[17]
16.00	19.50	3	Act,NaI,Ann.Gammas, 4P B-G counter	Al27(n,a)Na24		Pai	66	[17]
14.20	14.20	1	Act, NaI(Tl), Ann.Gammas	Cu65(n,2n)Cu64		Maslov+	72	[18]
14.60	14.60	1	Act, NaI(Tl), Ann.Gammas	Cu63(n,2n)Cu62		Araminowicz+	73	[19]
13.79	19.59	18	Act, NaI(Tl), Ann.Gammas, P-rec.tel.	1-H-1(n,n)1-H-1		Paulsen+	75	[20]
14.60	14.60	1	Act, Ge(Li), Ann. Gammas	Al27(n,a)Na24		Sigg	76	[21]
14.70	14.70	1	Act, Ge(Li), Ann.Gammas, P-rec.tel.	Al27(n,a)Na24g		Qaim+	76	[22]
13.50	14.78	6	Act, Ge(Li), Ann.Gammas	Al27(n,a)Na24	norm at 14.10 MeV	Csikai+	82	[23]
14.80	14.80	1	Act, Ge(Li), Ann.Gammas	Al27(n,a)Na24		Molla+	83	[24]
14.60	14.60	1	Act, Ge(Li), Ann.Gammas	T(d,n)He4 assoc.pt.		Zhou Muyao+	87	[25]
13.63	15.01	6	Act, Ge(Li), Ann.Gammas	Nb93(n,2n)Nb92m		Ikeda+	88	[26]
14.70	14.70	1	Act, HPGe and NaI(Tl), Ann.Gammas	Al27(n,a)Na24	norm at 14.10 MeV	Dighe+	91	[27]

calculation of the activation of structure materials in fusion facilities. As known the $^{54}Fe(n,2n)^{53m+g}Fe$ reaction is one of the sources of long-lived ^{53}Mn accumulation at irradiation of iron in fusion facility neutron spectrum.

THE EXPERIMENTAL DATA BASES FOR THE $^{46}Ti(n,2n)^{45}Ti$ AND $^{54}Fe(n,2n)^{53m+g}Fe$ REACTIONS CROSS-SECTIONS

The experimental data on the $^{46}Ti(n,2n)^{45}Ti$ reaction cross section have been reported since 1959. All the measurements have been carried out by activation technique. The list of experiments for the $^{46}Ti(n,2n)^{45}Ti$ reaction cross-section is given in Table 1. Columns 1-3 contain the lower and upper limits of the energy range under consideration in the experiment and the number of experimental points within this range.Methods of measurements of induced activity and neutron flux are given in columns 4, 5. In columns 6, 7 the name of the first author of the publication and the reference number are listed.

The original experimental data have been renormalized to new recommended standard cross-sections [2,9], quantum and positron yields [48].Corrections due to changes in half-lifes of radioactive nuclei are negligible.Of other introduced corrections (see Table 2) the most important are:

1. The errors of measured cross-sections declared by authors didn't include the error in average neutron energy. Respectively the contribution to cross-section error due to uncertainty in average neutron energy has been calculated on the basis of existing evaluation (JENDL-3) and added.
2. The analysis of the experimental data for other reactions cross-sections ($^{52}Cr(n,2n)$, $^{59}Co(n,2n)$) shows that the cross-sections measured by Ikeda et al. are systematically lower than the main bulk of the experimental data. In our opinion the most probable reason of this is systematical error in determination of average neutron energy. So we have shifted the cross-sections measured by Ikeda et al. to the left along the energy scale by 80 keV. This shift is within the error in average neutron energy declared by author.

TABLE 2. CROSS SECTION DATA FOR THE REACTION Ti46(n,2n)Ti45

NR.	E-NEUTR [MeV]	ERR.CENTR [MeV]	WIDTH [MeV]	SIGMA(ORIG) [MB]	ERROR(ORIG) [MB]	CORR.APPL.	SIGMA(CORR) [MB]	ERROR(CORR) [MB]	REFERENCE	
1	13.550	0.100	0.000	0.182	0.029	1 7 8	0.180	0.131	Ikeda+	88
2	13.600	0.060	0.200	1.600	0.200	1 8	1.600	0.900	Pai	66
3	13.650	0.100	0.000	0.894	0.059	1 7 8	0.886	0.372	Ikeda+	88
4	13.690	0.050	0.100	2.200	1.000	1 8	1.940	1.010	Prestwood+	61
5	13.770	0.070	0.200	7.500	0.600	1 8	7.600	2.000	Csikai+	82
6	13.880	0.050	0.100	7.000	1.000	1 8	6.680	1.280	Prestwood+	61
7	13.920	0.050	0.200	8.770	0.480	1 7 8	8.690	2.440	Ikeda+	88
8	14.050	0.050	0.250	16.200	1.700	3 8	16.000	2.900	Paulsen+	75
9	14.090	0.050	0.100	13.000	3.000	1 8	12.350	3.300	Prestwood+	61
10	14.100	0.060	0.300	14.000	1.000	8	14.000	2.400	Bormann+	65
11	14.100	0.070	0.200	17.700	1.300	1 8	17.900	3.500	Csikai+	82
12	14.130	0.100	0.000	13.300	1.100	8	13.300	3.400	Cevolani+	62
13	14.200	0.100	0.200	12.700	1.300	1 9	12.730	3.340	Maslov+	72
14	14.390	0.070	0.200	30.900	2.300	1 8	31.200	4.000	Csikai+	82
15	14.390	0.050	0.200	28.900	1.600	1 7 8	28.650	4.460	Ikeda+	88
16	14.400	0.060	0.300	31.800	2.417	1 3 8	31.100	3.639	Rayburn	61
17	14.420	0.054	0.270	28.300	2.400	3 8	28.000	3.200	Paulsen+	75
18	14.500	0.100	0.200	28.000	3.000	1 8	27.000	4.940	Prestwood+	61
19	14.600	0.050	0.000	42.800	3.600	1 9	42.400	6.000	Araminowicz+	73
20	14.600	0.040	0.000	36.900	2.500	1 8	36.850	3.260	Sigg	76
21	14.600	0.040	0.200	51.000	2.000	8	51.000	3.600	Zhou Muyao+	87
22	14.640	0.050	0.200	42.000	2.300	1 7 8	41.640	5.500	Ikeda+	88
23	14.660	0.070	0.200	42.000	3.200	1 8	42.400	5.100	Csikai+	82
24	14.700	0.000	0.000	54.000	0.000	1 9	51.600	7.700	Strain +	65
25	14.700	0.060	0.300	38.000	4.000	8	38.000	4.900	Qaim+	76
26	14.700	0.060	0.000	47.000	2.000	1 8	46.900	4.100	Dighe+	91
27	14.710	0.056	0.280	43.200	2.800	3 8	42.700	4.100	Paulsen+	75
28	14.780	0.070	0.200	50.200	3.800	1 8	50.700	5.600	Csikai+	82
29	14.800	0.180	0.900	50.400	8.000	1 8	41.700	10.500	Poularikas+	59
30	14.800	0.030	0.100	44.000	3.000	1 8	43.800	2.700	Pai	66

31	14.930	0.180	0.360	44.500	3.000	1 8	43.340	8.210	Prestwood+	61
32	14.930	0.050	0.200	54.900	3.000	1 7 8	54.430	5.620	Ikeda+	88
33	15.000	0.060	0.300	69.500	8.000	8	69.500	8.900	Bormann+	65
34	15.090	0.058	0.290	61.100	4.200	3 8	60.400	5.100	Paulsen+	75
35	15.370	0.058	0.290	90.500	5.700	3 8	89.400	6.700	Paulsen+	75
36	15.750	0.056	0.280	112.000	8.000	3 8	110.700	8.500	Paulsen+	75
37	15.990	0.056	0.280	117.000	7.000	3 8	115.600	7.500	Paulsen+	75
38	16.000	0.060	0.300	137.000	17.000	8	137.000	17.300	Bormann+	65
39	16.000	0.125	0.500	100.000	10.000	1 8	104.300	10.700	Pai	66
40	16.250	0.054	0.270	131.000	9.000	3 8	129.500	9.200	Paulsen+	75
41	16.420	0.054	0.270	142.000	8.000	3 8	140.300	8.200	Paulsen+	75
42	16.500	0.030	0.300	145.000	7.000	1 8	140.000	9.500	Prestwood+	61
43	16.610	0.052	0.260	149.000	9.000	3 8	147.200	9.100	Paulsen+	75
44	17.000	0.060	0.300	173.000	22.000	8	173.000	22.100	Bormann+	65
45	17.270	0.094	0.470	188.000	18.000	3 8	185.800	18.200	Paulsen+	75
46	17.300	0.175	0.700	170.000	14.000	1 8	168.300	12.300	Pai	66
47	17.750	0.090	0.450	197.000	14.000	3 8	194.700	14.100	Paulsen+	75
48	17.950	0.030	0.320	185.000	9.000	1 8	178.200	10.000	Prestwood+	61
49	18.000	0.060	0.300	202.000	25.000	8	202.000	25.100	Bormann+	65
50	18.330	0.082	0.410	218.000	15.000	3 8	215.400	15.000	Paulsen+	75
51	18.600	0.060	0.300	213.000	26.000	8	213.000	26.000	Bormann+	65
52	18.710	0.074	0.370	232.000	14.000	3 8	229.300	13.800	Paulsen+	75
53	19.130	0.062	0.310	226.000	14.000	3 8	223.300	13.900	Paulsen+	75
54	19.360	0.052	0.260	235.000	14.000	3 8	232.200	14.000	Paulsen+	75
55	19.500	0.050	0.200	250.000	25.000	1 8	243.900	22.000	Pai	66
56	19.590	0.046	0.230	239.000	14.000	3 8	236.200	14.000	Paulsen+	75
57	19.600	0.020	0.100	214.000	26.000	8	214.000	26.100	Bormann+	65
58	19.760	0.040	0.430	233.900	12.000	1 8	225.900	12.600	Prestwood+	61

CORRECTION CODES:

1) Cross-section renormalized to the new recommended values of reference cross section used in measurement.
3) Cross-section renormalized to the new recommended decay data (half-life, emission probability etc.).
6) Uncertainty in the half-life data are included in the total cross-section data error.
7) The center of energy resolution function was shifted. See text for details.
8) Uncertainties in neutron energy are included in the total cross-section data error.
9) The total error in the cross-section data was evaluated.

TABLE 3. SUMMARY OF EXPERIMENTS FOR THE REACTION Fe54(n,2n)Fe53g+m

ENERGY-RANGE [MeV]		NR. OF DATA POINTS	METHOD OF MEASUREMENT	MONITOR		REFERENCES		NR
14.10	14.10	1	Act, Prop. Counter, Beta+	Cu63(n,2n)Cu62		Allan	56	[28]
16.89	17.89	2	Act, GEMUC, B-	Fe56(n,p)Mn56	norm at 14.30 MeV	Terrell +	58	[29]
15.00	15.00	1	Act, Prop. Counter, Beta	Cu63(n,2n)Cu62		Depraz +	60	[30]
14.40	14.40	1	Act, Two NaI(Tl) ,Ann.Gammas Coinc.	Cu63(n,2n)Cu62		Rayburn	61	[11]
14.80	14.80	1	Act, B+	Al27(n,a)Na24 and Cu63(n,2n)Cu62		Chittenden+	61	[31]
14.10	14.10	1	Act,Boric acid counter+NaI(Tl),Gamma	NO INFORMATION GIVEN		Pollehn +	61	[32]
14.50	14.50	1	Act	Al27(n,a)Na24		Cross +	63	[33]
14.10	14.10	1	Act, Two NaI(Tl) ,Ann.Gammas Coinc.	Cu63(n,2n)Cu62		Carles	63	[34]
14.70	14.70	1	Act, NaI(Tl), Gamma	Cu63(n,2n)Cu62		Strain +	65	[14]
14.05	16.75	2	Act, NaI, Ann. Gamma	NO INFORMATION GIVEN		Salisbury+	65	[35]
14.60	14.60	1	Act, NaI(Tl), Gamma	Cu63(n,2n)Cu62		Csikai	65	[16]
13.87	17.40	10	Act, Solid Scint.,Ann.Gamma	Cu63(n,2n)Cu62	norm at 14.30 MeV	Andreev +	68	[36]
13.87	17.40	10	Act, Solid Scint.,Ann.Gammas Coinc.	Cu63(n,2n)Cu62	norm at 14.30 MeV	Andreev +	68	[36]
14.70	14.70	1	Act, Ge(Li), Ann.Gamma	Al27(n,p)Mg27		Qaim	72	[37]
14.60	14.60	1	Act, NaI(Tl), Gamma	Cu63(n,2n)Cu62		Araminowicz+	73	[19]
14.80	14.80	1	Act, Ge(Li), Ann.Gamma	Al27(n,p)Mg27		Sigg +	75	[38]
14.05	18.23	11	Act, NaI, Gamma and G-G coincidence	1-H-1(n,n)1-H-1	norm at 14.30 MeV	Bormann +	76	[39]
14.65	19.00	6	Act,4PI Beta PROPC coinc with NaI	Fe56(n,p)Mn56		Ryves +	78	[40]
15.30	18.95	6	Act,4 PI Beta-Gamma coinc. counter	1-H-1(n,n)1-H-1	norm at 14.77 MeV	Ryves +	78	[41]
14.70	14.70	1	Act, Ge(Li), Gamma	Al27(n,p)Mg27		Bahal +	84	[42]
13.95	14.64	6	Act, Ge(Li), Gamma	Al27(n,p)Mg27 and Al27(n,a)Na24		Greenwood+	85	[43]
14.60	14.60	1	Act, Ge(Li) , Gamma	T(d,n)He4 assoc.pt.	norm at 14.40 MeV	Zhou Muyao+	87	[25]
13.70	14.87	5	Act., HPGe, Gamma	Al27(n,p)Mg27		Katoh +	89	[44]
13.93	14.83	5	Act, Ge(Li), Gamma	Al27(n,p)Mg27		Viennot +	91	[45]

The corrected experimental data for the $^{46}Ti(n,2n)^{45}Ti$ reaction cross-section are consistent with exception of the energy range near threshold where excitation function increases.We discarded the cross-section measurement from the work [12] at energy 13.4 MeV being lower than reaction threshold.The cross-sections values given by Csikai at 13.5 MeV [23] and at 14.6 MeV [16], Paulsen et al. at 13.79 MeV [20], Molla et al. at 14.8 MeV [24] differ from the main bulk of experimental data more than two standard deviations. So they have been withdrawn also.

As to integral data there is the only experiment by Csikai et al. [49] which measured average $^{46}Ti(n,2n)^{45}Ti$ reaction cross-section in the ^{252}Cf spontaneous fission neutron spectrum. In our opinion measured average cross-section overestimates the true value by order approximately and can't be used as benchmark.

Unlike the $^{46}Ti(n,2n)^{45}Ti$ reaction cross-section the experimental data for the $^{54}Fe(n,2n)^{53m+g}Fe$ reaction cross-section are inconsistent and present a good object for demonstration of the power of theoretical model calculations and significance of preliminary analysis of the experimental data.

In the energy range from threshold to 16.63 MeV $^{54}Fe(n,2n)$ reaction leads to ^{53}Fe formation in the ground state.At neutron energies exceeding 16.63 MeV the 3.04 MeV isomer level of the ^{53}Fe ($J = 19/2^-$, $T_{1/2}$ = 2.58min) is excited. The transition from isomer state to ground one is realized with a probability of 100%.

The $^{54}Fe(n,2n)^{53m+g}Fe$ reaction cross-section measurements (first of which dates from 1956 [28]) cover range from 13.7 MeV to 19 MeV. The list of experiments for the $^{54}Fe(n,2n)^{53m+g}Fe$ reaction cross-section is given in Table 3. The original experimental data are shown in Fig.5,6. All the experimental data have been renormalized to new values of standard cross-sections [2,9], quantum, electron and positron yields [48]. The changes in half-lifes of radioactive nuclei have been taken into account by means of increasing of cross-section errors. The $^{27}Al(n,p)^{27}Mg$ cross-section extracted from [2] has been renormalized to new evaluation of this cross-section at E = 14.7 MeV [50].

In the energy range from threshold to 15 MeV results of recent Greenwood's and Viennot's experiments [43,45] are consistent with

TABLE 4. CROSS SECTION DATA FOR THE REACTION Fe54(n,2n)Fe53g+m

NR.	E-NEUTR [MeV]	ERR.CENTR [MeV]	WIDTH [MeV]	SIGMA(ORIG) [MB]	ERROR(ORIG) [MB]	CORR.APPL.	SIGMA(CORR) [MB]	ERROR(CORR) [MB]	REFERENCE	
1	13.700	0.050	0.000	0.220	0.198	1 8	0.210	0.210	Katoh +	89
2	13.930	0.030	0.120	0.800	0.800	1 8	0.760	0.760	Viennot +	91
3	13.950	0.070	0.200	0.680	0.095	1 6 8	0.650	0.233	Greenwood+	85
4	14.010	0.070	0.200	0.800	0.144	1 6 8	0.770	0.296	Greenwood+	85
5	14.010	0.150	0.000	2.100	0.441	1 8	2.050	1.181	Katoh +	89
6	14.050	0.210	1.050	2.830	0.050	6 8	2.830	1.920	Salisbury+	65
7	14.300	0.035	0.140	2.100	0.900	1 8	2.000	0.880	Viennot +	91
8	14.310	0.070	0.200	2.550	0.153	1 6 8	2.430	0.712	Greenwood+	85
9	14.350	0.150	0.000	5.300	1.060	1 8	5.220	2.036	Katoh +	89
10	14.460	0.070	0.200	3.700	0.111	1 6 8	3.530	0.960	Greenwood+	85
11	14.470	0.043	0.170	3.600	1.000	1 8	3.430	0.990	Viennot +	91
12	14.610	0.070	0.200	5.050	0.303	1 6 8	4.800	1.349	Greenwood+	85
13	14.640	0.070	0.200	5.850	0.175	1 6 8	5.560	1.501	Greenwood+	85
14	14.640	0.150	0.000	9.000	1.800	1 8	8.990	3.461	Katoh +	89
15	14.650	0.100	0.100	11.900	0.300	1 6 8	11.900	2.600	Ryves +	78
16	14.700	0.030	0.300	8.000	1.600	1 6 8	7.620	1.490	Qaim	72
17	14.700	0.040	0.000	7.900	0.700	1 3 6 8	7.600	1.700	Bahal +	84
18	14.730	0.058	0.230	7.100	1.800	1 8	6.730	1.870	Viennot +	91
19	14.800	0.090	0.900	7.900	0.800	1 6 8	8.000	1.700	Chittenden+	61
20	14.830	0.062	0.250	8.100	1.800	1 8	7.670	1.960	Viennot +	91
21	14.870	0.150	0.000	10.900	2.180	1 8	11.000	3.817	Katoh +	89
22	15.000	0.040	0.400	7.000	7.000	1	7.400	7.400	Depraz +	60
23	15.300	0.200	0.300	24.000	2.300	8	24.000	7.300	Ryves +	78
24	16.060	0.300	0.300	44.700	2.300	1 6 8	43.300	8.300	Ryves +	78
25	16.510	0.250	0.250	56.000	3.700	1 6 8	55.300	7.300	Ryves +	78
26	16.550	0.100	0.240	58.000	12.400	8	58.000	15.900	Ryves +	78
27	16.750	0.110	0.550	50.400	5.000	6 8	50.400	6.200	Salisbury+	65
28	17.000	0.100	0.220	49.000	6.500	8	49.000	10.600	Ryves +	78
29	17.350	0.200	0.200	73.100	2.900	1 6 8	73.000	6.400	Ryves +	78
30	17.370	0.100	0.220	65.000	6.000	8	65.000	12.600	Ryves +	78
31	17.860	0.100	0.210	86.000	9.100	8	86.000	17.100	Ryves +	78
32	18.060	0.190	0.190	87.100	4.300	1 6 8	86.800	5.700	Ryves +	78
33	18.950	0.100	0.210	85.000	5.900	8	85.000	15.400	Ryves +	78
34	19.000	0.190	0.190	98.700	5.900	1 6 8	98.200	5.700	Ryves +	78

Correction codes are the same is in the TABLE 2 each other.The measurements of Kato [44] don't contradict to Greenwood's and Viennot's data but exceed them below 14.7 MeV. The measurements of Qaim [37] and Bahal [42] at energy 14.7 MeV coincide practically. They are in agreement with results of experiments described above also. The same is true for measurements reported by Chittenden at 14.8 MeV [31] and Depraz at 15.0 MeV [30]. In spite of corrections the results of many experiments in the energy range from threshold to 15 MeV [11,14,16,19,25,28,29,32-34,36,38,39] are inconsistent with both theoretical model calculations [47] and measurements considered above. In particular cross-sections measured in those experiments are higher by a factor of 2 to 4 than Greenwood's and Viennot's data.By this reason they have been disregarded.

In the energy range 15 - 19 MeV there are three trends in the cross-section behavior (the data of Ryves [40],[41], Bormann [39], Andreev [36]). The measurements of Ryves [40,41] have been carried out by two different techniques (in point of view of both neutron flux monitoring and induced activity measurement).Besides the cross sections given by Ryves are in agreement with theoretical model calculations [47].As to Bormann's data they are inconsistent with already accepted experimental cross-sections (below 15 MeV) and theoretical model calculations [47] (above 17 MeV). In its turn Andreev's data exceed the cross-sections reported by Ryves and results of theoretical model calculations by a factor of 2.So Bormann's and Andreev's data have been withdrawn. The resulting experimental data base for the $^{54}Fe(n,2n)^{53m+g}Fe$ reaction cross-section is given in Table 4. It includes information about average energy and energy spread of incident neutrons, the error of average neutron energy, cross-sections values and their errors given by authors, corrected cross-sections and their errors.

For all the experimental sets included in data bases the analysis of cross-section error components has been performed and average correlation coefficient for each experimental data set (see Tables 5,6) has been calculated.

Table 5. Average correlation coefficients (F-corr) for the experimental data used for the evaluation of the Ti46(n,2n)Ti45 reaction excitation function.

Experimental data			F-corr	Experimental data			F-corr
1.	Poularikas+	59	0.00	10.	Maslov+	72	0.00
2.	Prestwood+	61a	0.17	11.	Araminowicz+	73	0.00
3.	Prestwood+	61b	0.54	12.	Paulsen+	75	0.46
4.	Rayburn	61	0.00	13.	Sigg	76	0.00
5.	Cevolani+	62	0.00	14.	Qaim+	76	0.00
6.	Bormann+	65	0.31	15.	Csikai+	82	0.13
7.	Strain +	65	0.00	16.	Zhou Muyao+	87	0.00
8.	Pai	66a	0.42	17.	Ikeda+	88	0.66
9.	Pai	66b	0.32	18.	Dighe+	91	0.00

Table 6. Average correlation coefficients (F-corr) for the experimental data used for the evaluation of the Fe54(n,2n)Fe53g+m reaction excitation function.

Experimental data			F-corr	Experimental data			F-corr
1.	Chittenden+	61	0.00	6.	Bahal +	84	0.00
2.	Salisbury+	65	0.30	7.	Greenwood+	85	0.80
3.	Qaim+	72	0.00	8.	Katoh +	89	0.69
4.	Ryves +	78a	0.66	9.	Viennot +	91	0.37
5.	Ryves +	78b	0.61				

STATISTICAL ANALYSIS OF THE EXPERIMENTAL DATA AND RESULTS OF CALCULATIONS

The method of statistical analysis of the correlated experimental data was described in detail in [46]. Here we will outline only the main features of the method.

The experimental data are analyzed within the framework of non-linear regression model. The rational function

Table 7. Evaluated group cross-sections for the $^{46}Ti(n,2n)^{45}Ti$ reaction.

ENERGY GROUP [MeV] to [MeV]		GROUP NUMBER	CROSS-SECTION [mb]	ERROR [mb]	ERROR [%]
13.60	13.70	1	1.34	0.23	16.98
13.70	13.90	2	4.31	0.41	9.60
13.90	14.10	3	10.13	0.57	5.66
14.10	14.30	4	17.86	0.72	4.06
14.30	14.50	5	27.06	0.88	3.27
14.50	14.70	6	37.33	1.04	2.79
14.70	14.90	7	48.33	1.21	2.50
14.90	15.10	8	59.73	1.41	2.36
15.10	15.30	9	71.28	1.67	2.34
15.30	15.50	10	82.78	1.99	2.40
15.50	16.00	11	102.25	2.61	2.55
16.00	16.50	12	128.07	3.47	2.71
16.50	17.00	13	150.91	4.12	2.73
17.00	17.50	14	170.72	4.54	2.66
17.50	18.00	15	187.75	4.84	2.58
18.00	19.00	16	208.62	5.30	2.54
19.00	20.00	17	230.35	6.44	2.80

$$f(E) = C + \sum_{i=1}^{l_1} \frac{a_i}{E-p_i} + \sum_{k=1}^{l_2} \frac{\alpha_k(E-\varepsilon_k)+\beta_k}{(E-\varepsilon_k)^2+\gamma_k^2} \quad (1)$$

is used as model function. The minimized functional has the form:

$$S = (\vec{\sigma} - \vec{f})^T V^{-1} (\vec{\sigma} - \vec{f}) \quad (2)$$

In formulas (1) and (2) C, a_i, p_i, α_k, β_k, ε_k, γ_k - parameters to be estimated, $\vec{\sigma}$ and V - vector and covariance matrix of measured cross-sections, superscript T denotes a transpose. For calculation of covariance matrix of the estimated parameters W the following formula has been used

$$W = \frac{S}{n-L} (X^T V^{-1} X)^{-1}$$

where n - the total number of measured cross-sections, L - the number of parameters of the rational function, X is a matrix of the sensitivity coefficients of the rational function to a variation of parameters.

The results of evaluation are shown in Fig.1-10. The evaluated curve for the $^{54}Fe(n,2n)^{53m+g}Fe$ reaction has 5 parameters in representation (1) (energy in MeV, cross-section in mb, energy range 13.7 - 20 MeV): α_1=329.74, β_1=-545.26, ε_1=15.804, γ_1=3.4700,

Table 8. Evaluated group cross-sections for the $^{54}Fe(n,2n)^{53m+g}Fe$ reaction.

ENERGY GROUP [MeV] to [MeV]		GROUP NUMBER	CROSS-SECTION [mb]	ERROR [mb]	ERROR [%]
13.70	13.90	1	0.39	0.13	33.45
13.90	14.10	2	0.96	0.19	19.41
14.10	14.30	3	2.00	0.27	13.61
14.30	14.50	4	3.55	0.38	10.59
14.50	14.70	5	5.66	0.51	9.06
14.70	14.90	6	8.35	0.69	8.23
14.90	15.10	7	11.63	0.89	7.69
15.10	15.30	8	15.49	1.13	7.26
15.30	15.50	9	19.90	1.37	6.88
15.50	16.00	10	28.81	1.80	6.26
16.00	16.50	11	42.95	2.44	5.68
16.50	17.00	12	57.38	3.00	5.23
17.00	17.50	13	70.54	3.32	4.71
17.50	18.00	14	81.46	3.32	4.08
18.00	19.00	15	92.92	3.14	3.37
19.00	20.00	16	101.47	4.27	4.20

Table 9. Correlation matrix of evaluated group cross-sections for the $^{46}Ti(n,2n)^{45}Ti$ reaction. Correlations are given in percentages. NR - the group number.

ENERGY GROUP [MeV]		NR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
13.60	13.70	1	100																
13.70	13.90	2	91	100															
13.90	14.10	3	78	91	100														
14.10	14.30	4	56	73	92	100													
14.30	14.50	5	36	54	80	95	100												
14.50	14.70	6	23	40	66	86	96	100											
14.70	14.90	7	16	29	53	74	88	97	100										
14.90	15.10	8	13	22	40	60	75	88	97	100									
15.10	15.30	9	13	17	29	45	61	76	89	97	100								
15.30	15.50	10	15	15	21	32	47	64	80	92	98	100							
15.50	16.00	11	19	14	12	17	29	46	64	80	91	97	100						
16.00	16.50	12	23	15	7	7	16	31	50	68	82	91	98	100					
16.50	17.00	13	26	17	7	4	11	25	43	61	75	85	94	99	100				
17.00	17.50	14	26	19	9	6	11	23	39	56	70	80	89	96	99	100			
17.50	18.00	15	25	20	13	10	14	24	38	53	65	73	82	89	95	98	100		
18.00	19.00	16	20	19	18	19	22	29	38	47	54	59	66	73	80	88	95	100	
19.00	20.00	17	9	14	22	28	32	34	35	36	37	37	38	44	53	64	76	92	100

C=75.484. The $^{46}Ti(n,2n)^{45}Ti$ evaluated reaction cross-section has 5 parameters too (energy range 13.60 - 20 MeV): α_1=-424.23, β_1=-2878.4, ε_1=12.808, γ_1=2.9882, C=337.02.

Table 10. Correlation matrix of evaluated group cross-sections for the $^{54}Fe(n,2n)^{53m+g}Fe$ reaction. Correlations are given in percentages. NR - the group number.

ENERGY GROUP [MeV]		NR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
13.70	13.90	1	100															
13.90	14.10	2	19	100														
14.10	14.30	3	26	67	100													
14.30	14.50	4	31	66	82	100												
14.50	14.70	5	34	59	77	89	100											
14.70	14.90	6	34	50	68	84	94	100										
14.90	15.10	7	34	42	59	77	90	96	100									
15.10	15.30	8	32	35	51	70	85	93	97	100								
15.30	15.50	9	30	29	44	63	79	89	95	98	100							
15.50	16.00	10	26	21	33	50	66	78	86	92	96	100						
16.00	16.50	11	19	14	21	34	47	58	68	77	84	94	100					
16.50	17.00	12	13	11	14	21	30	39	48	58	67	82	96	100				
17.00	17.50	13	8	9	10	13	18	25	33	42	51	69	87	97	100			
17.50	18.00	14	6	10	9	10	13	17	24	32	40	57	77	90	97	100		
18.00	19.00	15	7	10	12	14	16	19	22	26	30	39	51	62	73	86	100	
19.00	20.00	16	9	7	13	21	25	27	26	23	20	13	5	4	11	28	72	100

The values of minimized functional S equal to 1.02 and 1.09 respectively. In energy range from threshold to 13.7 MeV (for the $^{54}Fe(n,2n)^{53m+g}Fe$ reaction) and from threshold to 13.60 MeV (for the $^{46}Ti(n,2n)^{45}Ti$ reaction) linear interpolation must be used.

As seen from Fig.1,2 and Fig.7,8 there is essential difference (especially in the important energy range from threshold to 15 MeV) between our evaluation and the JENDL-3 and ENDF/B-6 evaluations. Our curves are systematically lower the JENDL-3 and ENDF/B-6 evaluations. In our opinion the reason of this deviation is in the difference of the used experimental data bases. Our evaluations are oriented on recent measurements carried out by Ikeda et al.[26] (for the $^{46}Ti(n,2n)^{45}Ti$ reaction), Viennot et al.[45], Katoh et al.[44], Greenwood et al.[43] (for the $^{54}Fe(n,2n)^{53m+g}Fe$ reaction).

Fig.3,4 and Fig.9,10 illustrate the variation of uncertainty of the evaluated cross-sections via energy of incident neutrons. According to Fig.3,4 the $^{46}Ti(n,2n)^{45}Ti$ reaction cross-section is known to an accuracy of 20.0 - 4.0% in the range from threshold to 15 MeV and to about 4% in the range 15 - 20 MeV. The $^{54}Fe(n,2n)$ reaction cross-section is known to an accuracy of 33.0 - 11.0% in

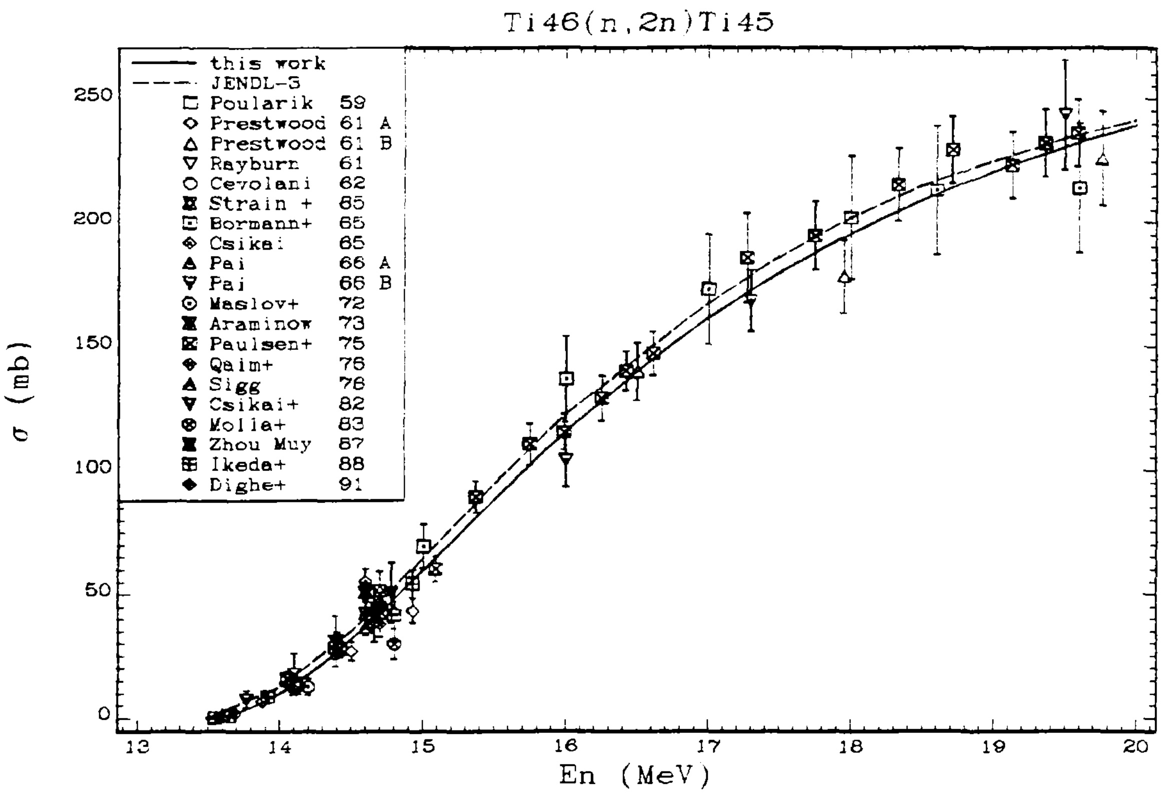

Fig. 1 The evaluated cross-section in comparison with the experimental data and the JENDL-3 evaluation in energy range from threshold to 20 MeV.

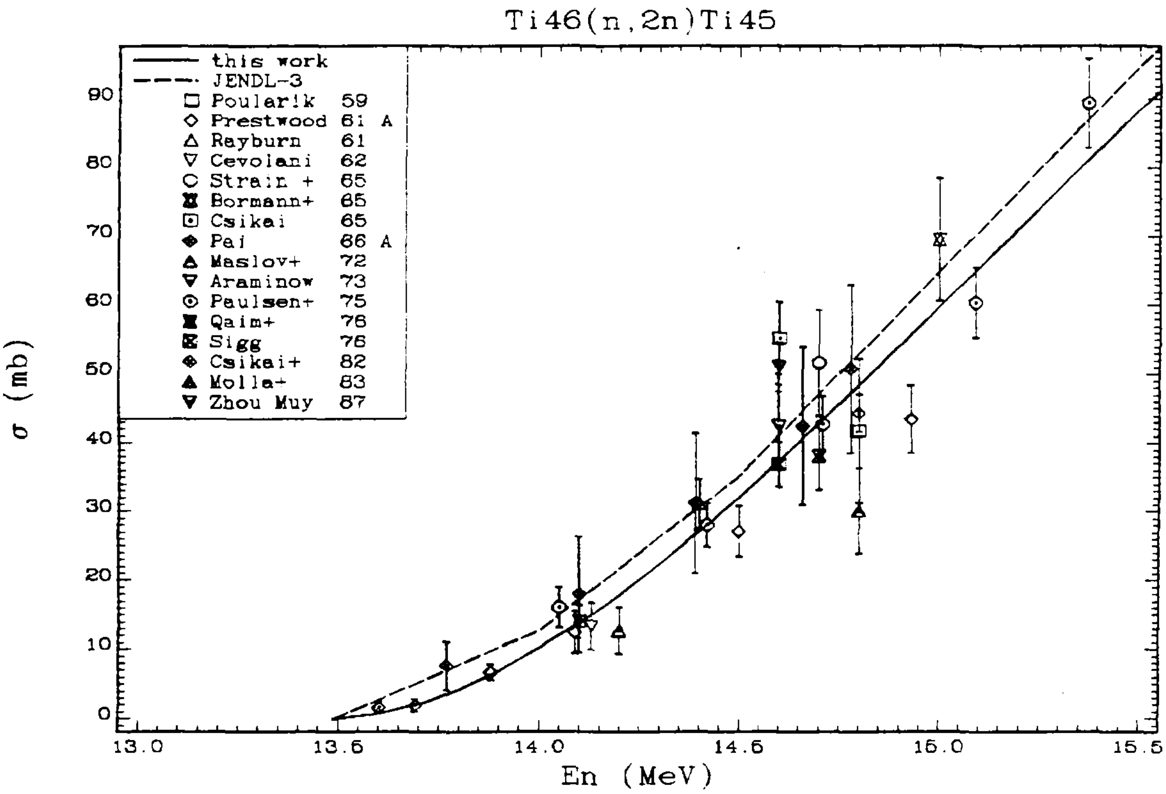

Fig. 2 The evaluated cross-section in comparison with the experimental data and the JENDL-3 evaluation in energy range from threshold to 15 MeV.

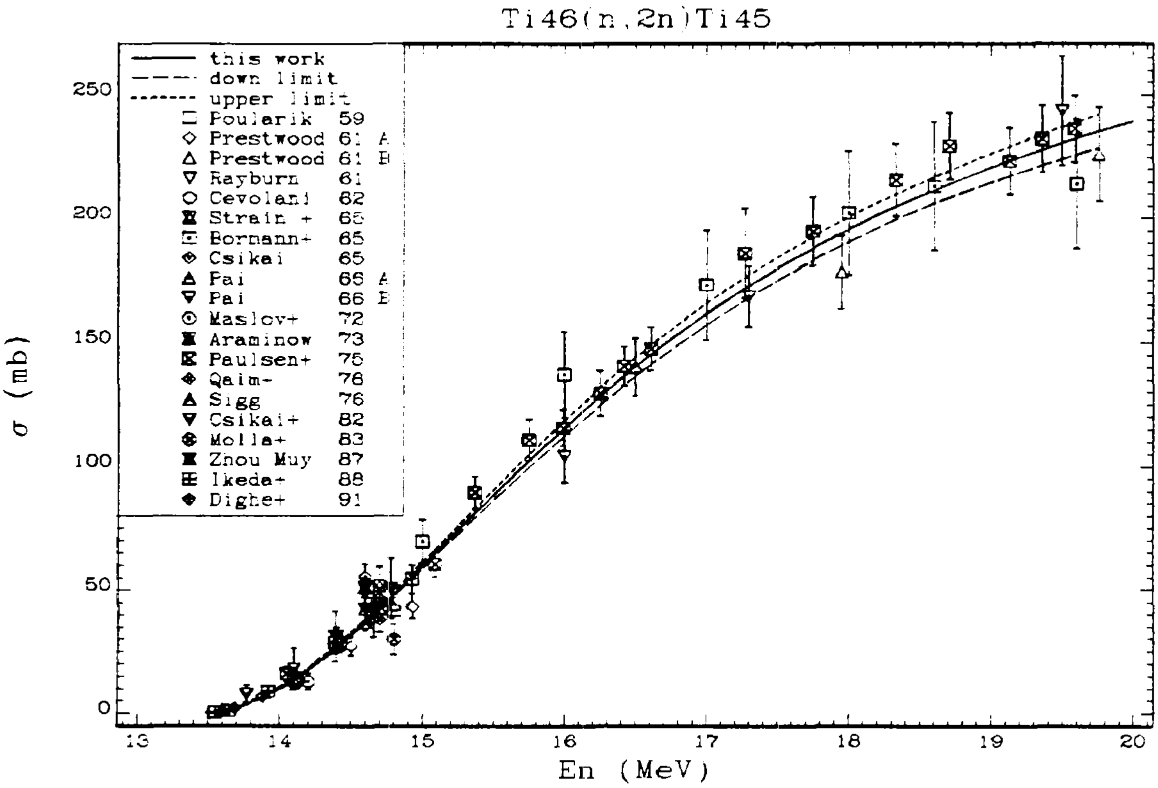

Fig. 3 The results of cross−section evaluation from this work in the energy range from threshold to 20 MeV (dashed lines display 1 б error of evaluation).

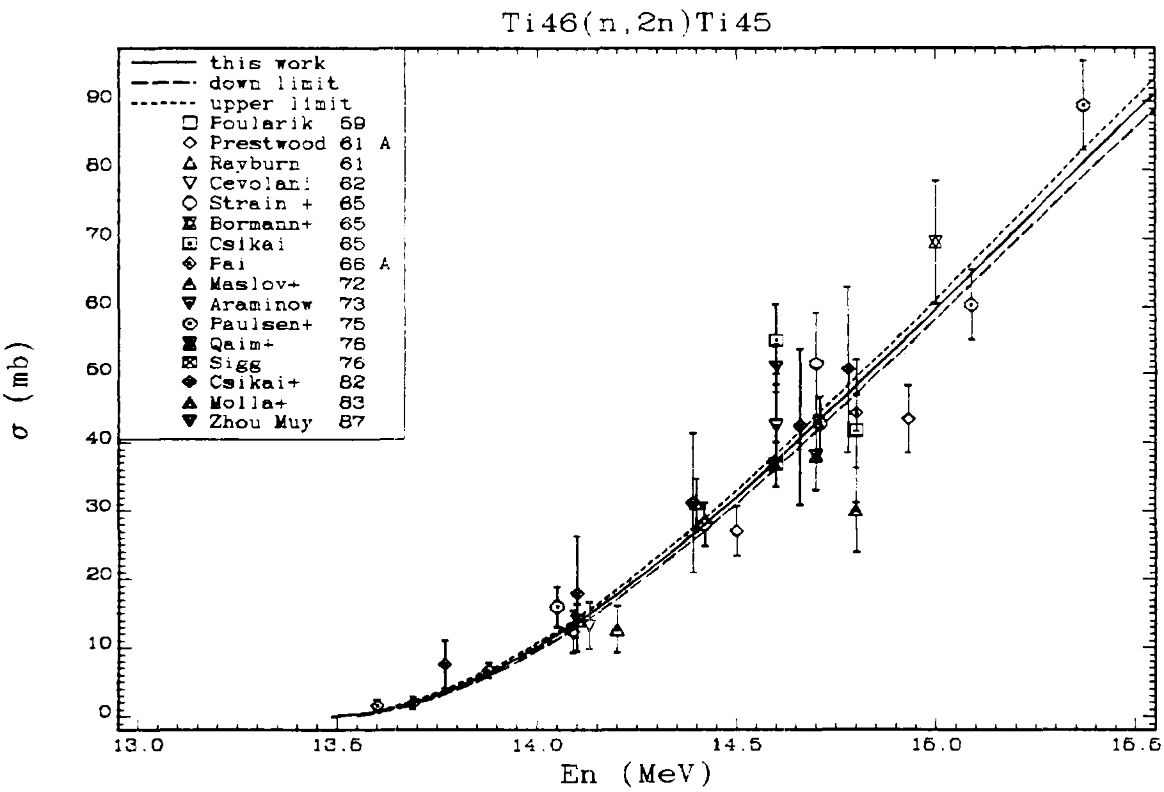

Fig. 4 The results of cross−section evaluation from this work in the energy range from threshold to 15 MeV (dashed lines display 1 б error of evaluation).

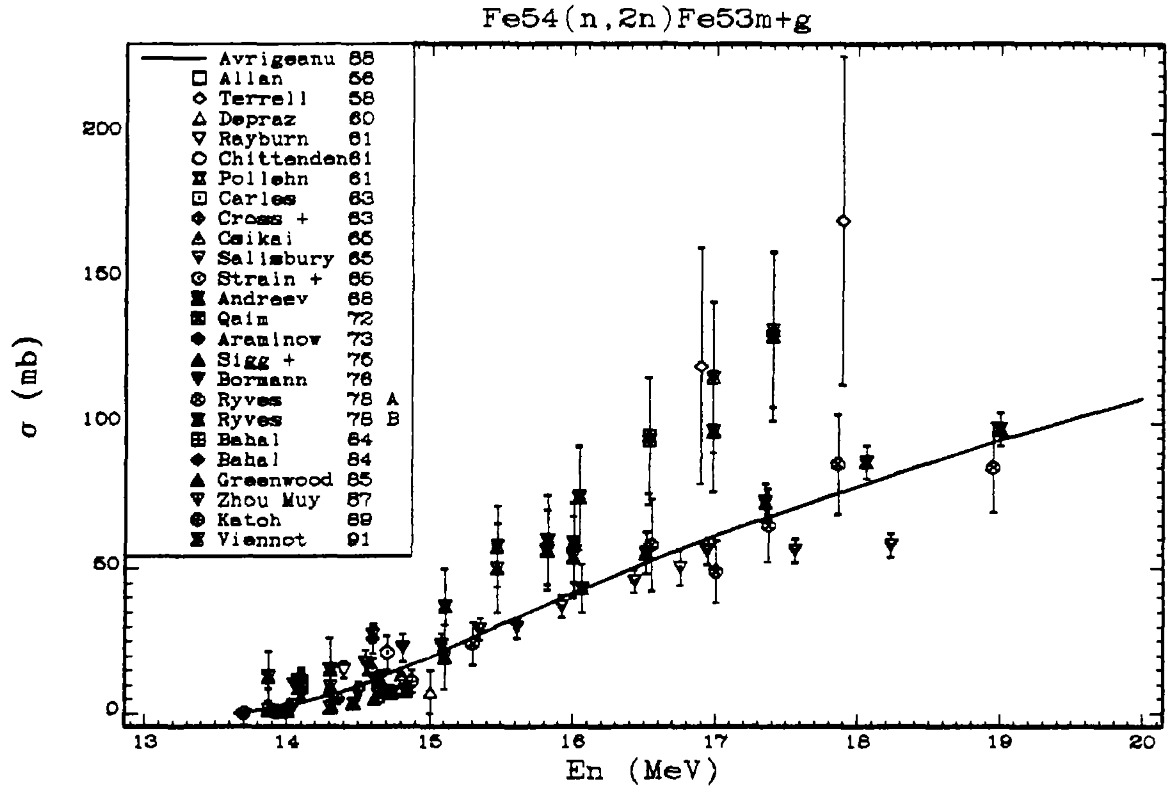

Fig. 5 The original experimental data and the results of theoretical model calculations of M.Avrigeanu /47/ for the Fe54(n,2n)Fe53m+g reaction excitation function in energy range from threshold to 20 MeV.

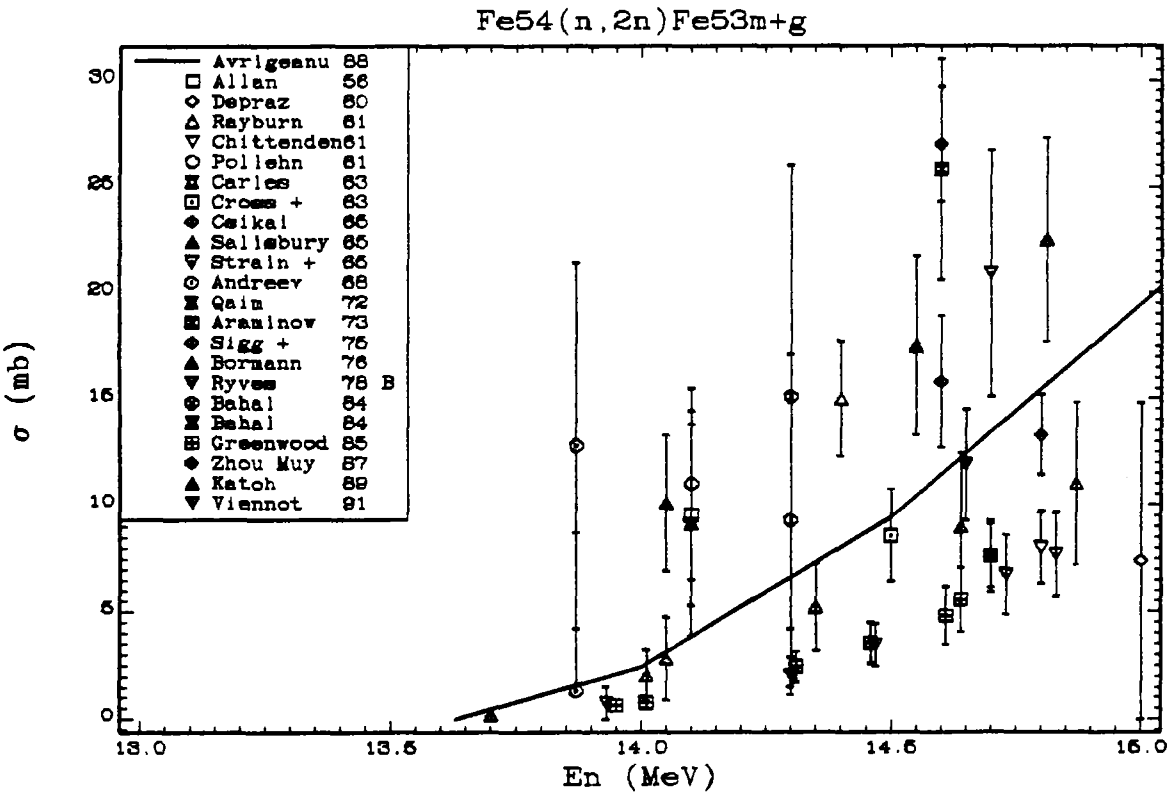

Fig. 6 The original experimental data and the results of theoretical model calculations of M.Avrigeanu /47/ for the Fe54(n,2n)Fe53m+g reaction excitation function in energy range from threshold to 15 MeV.

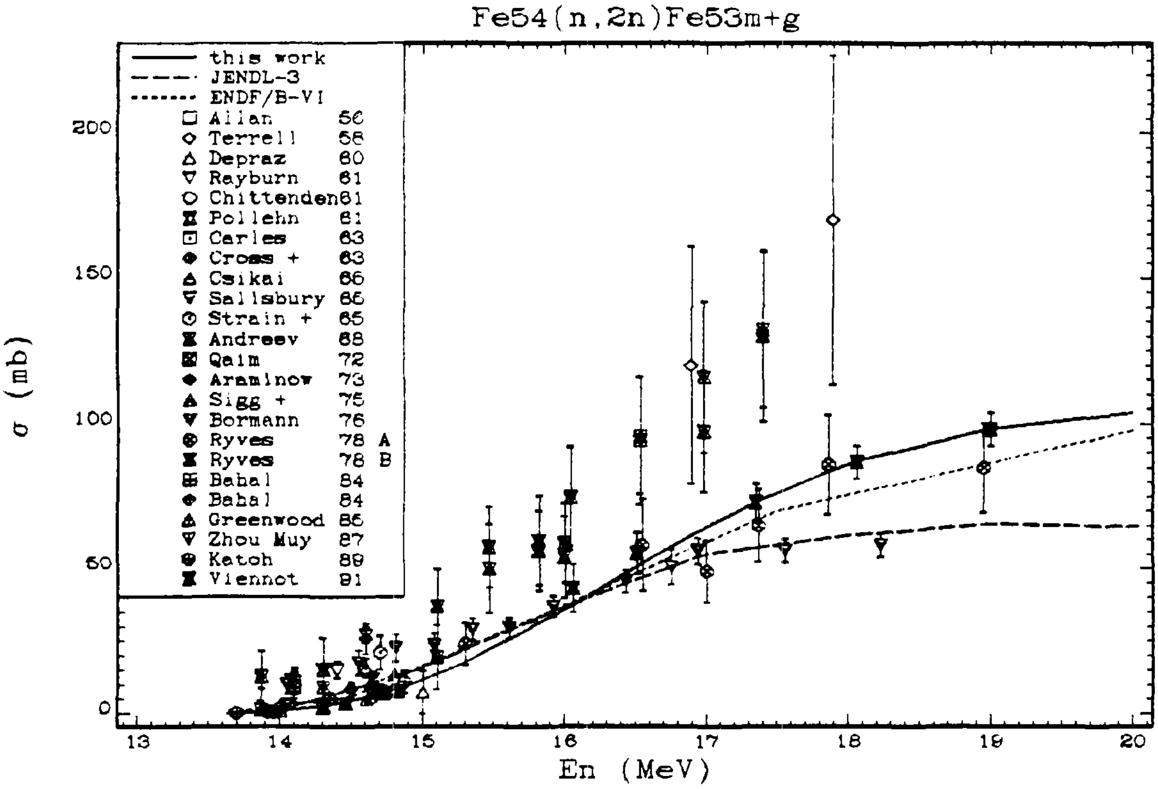

Fig. 7 The evaluated cross-section in comparison with the experimental data and the JENDL-3 and ENDF/B-VI evaluations in energy range from threshold to 20 MeV.

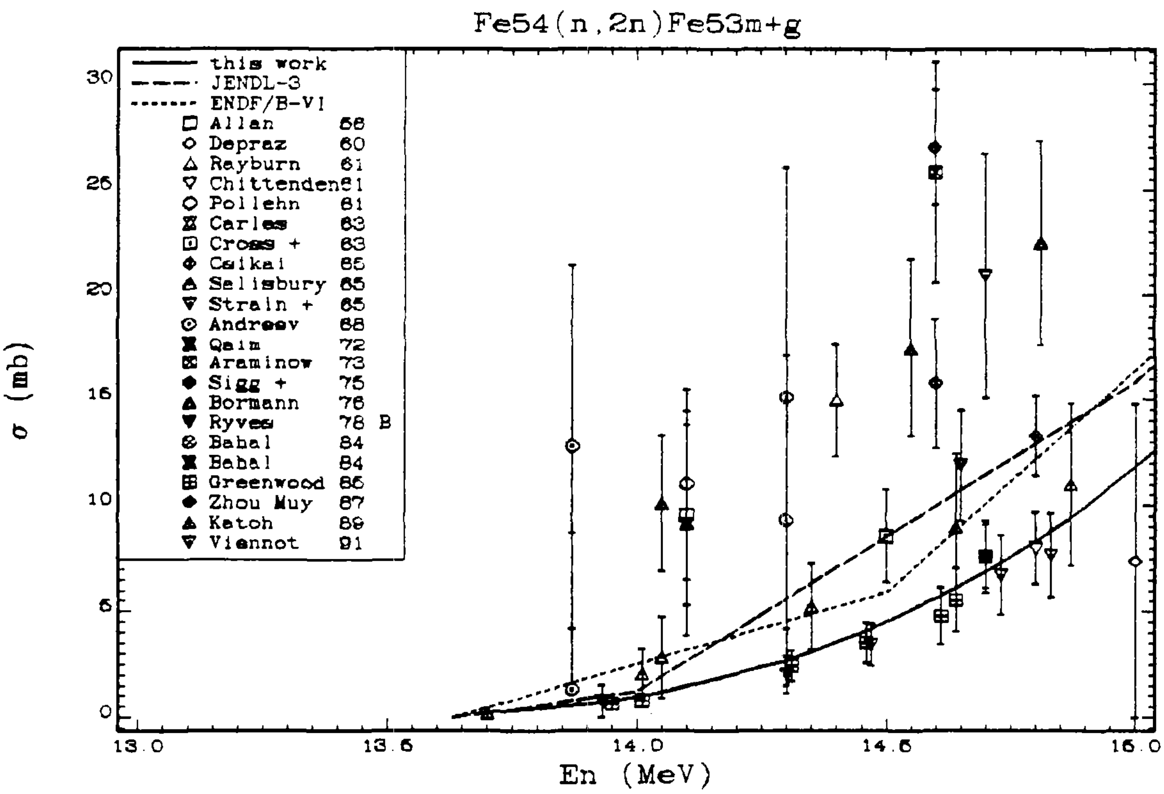

Fig. 8 The evaluated cross-section in comparison with the experimental data and the JENDL-3 and ENDF/B-VI evaluations in energy range from threshold to 15 MeV.

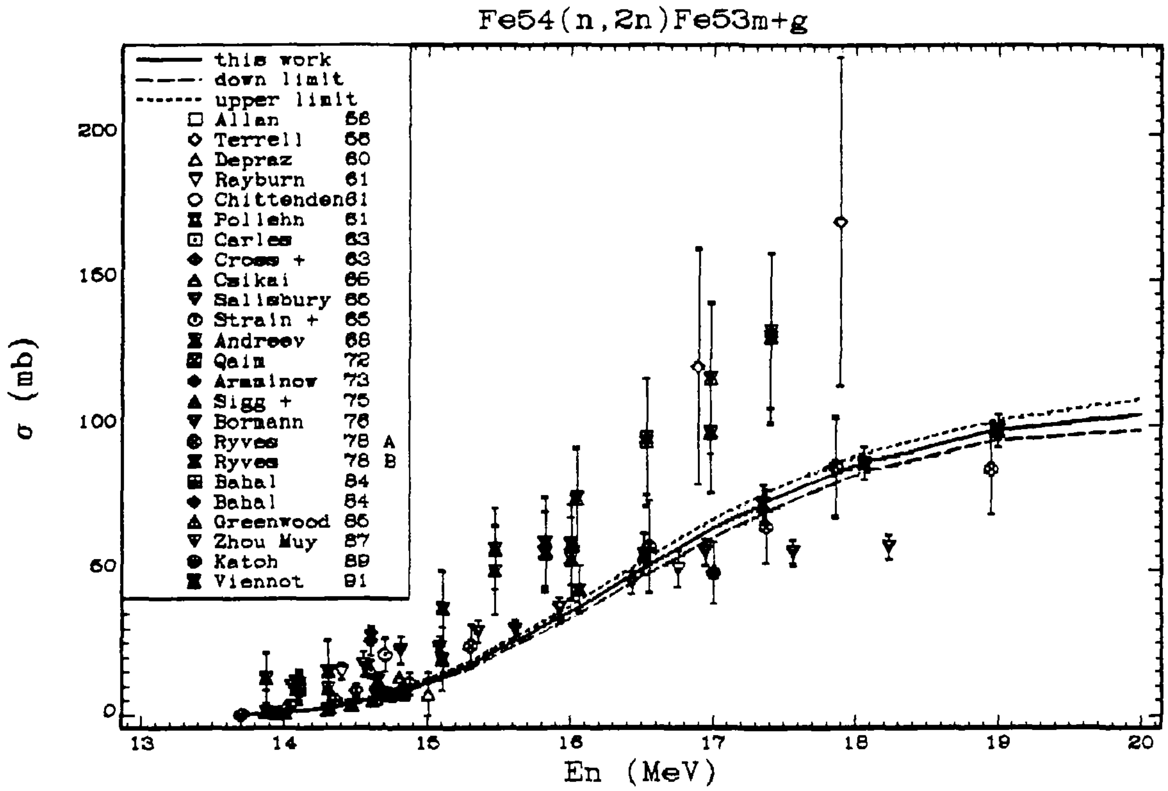

Fig. 9 The results of cross-section evaluation from this work in the energy range from threshold to 20 MeV (dashed lines display 1 standard deviation error of evaluation)

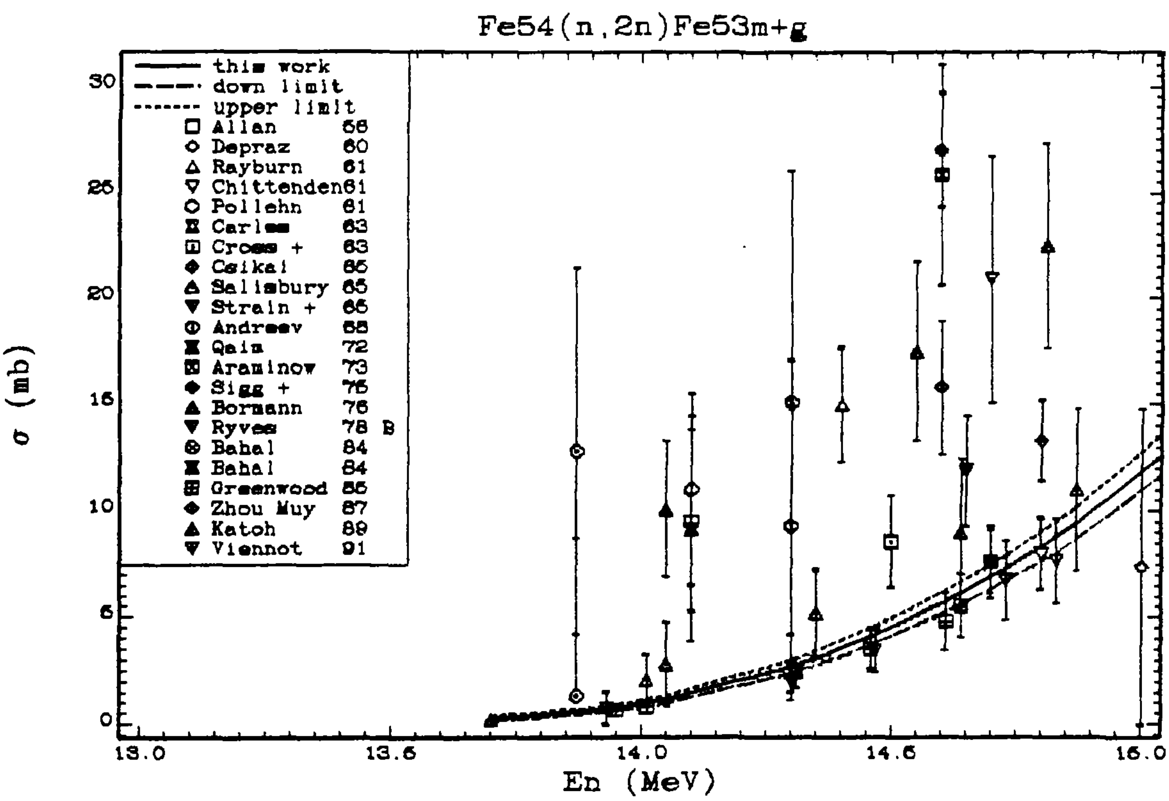

Fig.10 The results of cross-section evaluation from this work in the energy range from threshold to 15 MeV (dashed lines display 1 standard deviation error of evaluation)

the range from threshold to 14.5 MeV and 11.0 - 3.5% in the range 14.5 - 20 MeV. Evaluated group cross-sections and their correlations are given in Tables 7-10.

SUMMARY

1. The experimental data bases comprising the results of the $^{46}Ti(n,2n)^{45}Ti$ and $^{54}Fe(n,2n)^{53m+g}Fe$ reaction cross-section measurements up to January 1993 have been compiled. After critical review of the experimental data and introduction of corrections the resulting data bases have been formed.
2. The evaluations of the $^{46}Ti(n,2n)^{45}Ti$ and $^{54}Fe(n,2n)^{53m+g}Fe$ reaction cross-sections were carried out on the basis of Pade-approximation with taking the correlation of experimental data into account. The evaluated cross-sections are presented in the analytical form convenient for the use in applications. The uncertainty of evaluated cross-sections in energy range 13.7 - 14.5 MeV (critically important for fusion application) is 33 - 11 % for the $^{54}Fe(n,2n)^{53m+g}Fe$ reaction and 20-4 % for the $^{46}Ti(n,2n)^{45}Ti$ reaction. It is evident that new precise measurements with high resolution would be desirable in the energy range 13.7 - 14.5 MeV.
3. The files of evaluated cross-sections (File 3) and covariances (File 33) were prepared in the ENDF/B-6 format.

REFERENCES

1. E.I.Grigor'ev Neutron Activation Detectors. State of the art and trends. Proc. of IAEA interregional training course " The applications of nuclear data and measurement techniques in nuclear reactor and personal neutron dosimetry", 15 June- 10 July 1992. IPPE, Obninsk, Russia.
2. N.P.Kocherov, P.McLaughlin The International Reactor Dosimetry File (IRDF-90), Report IAEA-NDS-141, Vienna, August 1990.
3. M.Nakazawa e.a. JENDL Dosimetry File. Report JAERY 1325, March 1992.
4. Cai Dunjiu Evaluation of Cross-sections for Dosimetry Reactions. Report INDC(CPK)-024, IAEA, Vienna, Oct.1991.
5. U.S. National Nuclear Data Center, Computer Database Evaluated Nuclear Data File ENDF/B-6, Brookhaven, 1990

6. V.N.Manokhin, A.B.Pashchenko, V.I.Plyaskin e.a. Activation Cross-Sections Induced by Fast Neutrons. Handbook on Nuclear Activation Data, Vienna, 1987, p.305-411.
7. K.Shibata e.a. Japanese Evaluated nuclear Data Library, version-3. Report JAERI-1319, 1990.
8. J.Kopecky, H.Gruppelaar Nuclear Data for Science and Technology. Proc. of International Conf. 13-17 May 1991, Julich, FRG, p.245-248.
9. "Nuclear Data Standards for Nuclear Measurements", Ed. H.Conde, OECD, Paris, 1992.
10. A.Poularikas, R.W.Fink Physical Review, v.115, p.989, 1959
11. L.A.Rayburn Physical Review, v.122, p.168, 1961
12. R.J.Prestwood, B.P.Bayhurst Physical Review, v.121, p.1438, March 1961
13. M.Cevolani, S.Petralla J,NC, v.26, p.1328, Dec.1962
14. J.E.Strain, W.J.Ross Report ORNL-3672, Jan.1965
15. M.Bormann e.a. Nuclear Physics, v.63, p.438, March 1965
16. J.Csikai Progress Report EANDC-50S, v.2, p.102, July 1965
17. H.L.Pai Canadian J. of Physics, v.44, p.2337, 1966
18. G.N.Maslov e.a. R,Yadernye Konstanty, Nr.9, p.50, 1972
19. J.Araminowicz,J.Dresler Progress Rep. INR-1464, p.14, May 1973
20. A.Paulsen e.a Atomkernenergie , v.26, p.34, Aug.1975
21. R.A.Sigg J,DA/B, v.37, p.2237, Nov.1976
22. S.M.Qaim, N.I.Molla Conf,76GARMIS,, p.589, June 1976
23. J.Csikai Proc. of Int.Conf. on Nuclear Data for Science and Technology, Antwerpen, 6-10 Sep.1982, p.414, Reidel Publ.Comp.
24. N.T.Molla e.a. Progress Report INDC(BAN)-002, p.1, Feb.1983
25. Zhou Muyao e.a. Chinese J. of Nuclear Physics, v.9, p.34, Feb.1987.
26. Y.Ikeda e.a. Report JAERI-1312, 1988
27. P.M.Dighe e.a. Indian J. of Pure and Applied Physics, v.29, p.665, Oct.1991
28. D.L.Allan J,Proc.Phys.Soc., v.70, p.195, 1956
29. J.Terrell,D.M.Holm Physical Review, v.109, p.2031, 1958
30. M.J.Depraz e.a. J,JPR, v.21, p.377, May 1960
31. D.M.Chittenden e.a. Physical Review, v.122, p.860, 1961
32. H.Pollehn,H.Neuert Zeitschrift f.Naturforschung, sect.A, v.16, p.227, 1961

33. W.G.Cross e.a. Progress Rep. EANDC(CAN)-16, p., Jan.1963
34. C.Carles J,CR, v.257, p.659, July 1963
35. S.R.Salisbury,R.A.Chalmers. Physical Review,v.B140,p.305,1965.
36. M.F.Andreev,V.I.Serov Jadernaja Fizika (Sov.), v.7, n.4, p.745, Apr.1968
37. S.M.Qaim Nuclear Physics, v.A185, p.614, May 1972
38. R.A.Sigg,P.K.Kuroda J, Inorg.Nucl.Chem., v.37, p.631, Mar.1975
39. M.Bormann e.a. Zeitsch. f. Physik, sect.A, v.277, p.203, June 1976
40. T.B.Ryves e.a. J. of Physics, pt.G, v.4, n.11, p.1783, 1978
41. T.B.Ryves e.a. J. Metrologia, v.14, n.3, p.127, June 1978
42. B.M.Bahal,R.Pepelnik Report GKSS-84-E-, 1984
43. L.R.Greenwood,R.K.Smither Proceedings of Int. Conf. Nuclear Data for Basic and Applied Science, Santa Fe, New Mexico 13-17 May 1985, v.1, p.163
44. T.Katoh e.a. Report JAERI-M-89-083, 1989
45. M.Viennot e.a. Nuclear Science and Engineering, v.108, p.289, July 1991
46. S.A.Badikov, N.S.Rabotnov, K.I.Zolotarev. In: Proc. of NEANSC Specialist's Meeting on Evaluation and Processing of Covariance Data, 7-9 October 1992, Oak Ridge, USA, p.105,OECD,Paris(1993).
47. M.Avrigeanu e.a. Z.Phys.A-Atomic Nuclei, v.329, p.177, 1988.
48. E.Browne, R.B.Firestone. Table of Radioactive Isotopes, John Wiley & Sons, New York, 1986.
49. J.Csikai, Z.Dezso. In: Proc. of 4th All Union Conf. on Neutron Physics, Kiev, 18-22 April 1977, v.3, p.32.
50. T.B.Ryves. "Annals of Nuclear Energy", v.16, N.6, 1989.