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INDC **INTERNATIONAL NUCLEAR DATA COMMITTEE**

THE IAEA CO-ORDINATED RESEARCH PROGRAMME ON

ACTIVATION CROSS SECTIONS FOR THE GENERATION OF LONG-LIVED RADIONUCLIDES OF IMPORTANCE IN FUSION REACTOR TECHNOLOGY

FINAL REPORT

prepared at the final CRP Meeting in St. Petersburg, Russia
19 - 23 June 1995

Edited by
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IAEA Nuclear Data Section
Vienna, Austria

July 1997

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Abstract

The present report summarizes the final results of the IAEA Co-ordinated Research Programme on "Activation Cross Sections for the Generation of Long-lived Radionuclides of Importance in Fusion Reactor Technology". The goal of the CRP was to obtain reliable information (experimental and evaluated) for 16 long-lived activation reactions of special importance to fusion reactor technology. By limiting the scope of the CRP to just 16 reactions it was possible to establish a very effective focus to the joint effort of many laboratories that has led to the generation of a set of valuable new data which provide satisfactory answers to several questions of technological concern to fusion.

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Foreword

Activation of reactor materials due to the neutron field generated by the 14 MeV deuterium-tritium neutrons is a principal issue concerning the development of fusion as a long-term energy source. It will impact the development of reactor technologies relevant to safety, maintenance, and waste disposal. Availability and quality of key activation data are very important for the assessment of solutions to the various activation concerns. Considering the current needs and original requests of the fusion community to meet the design requirements the IAEA formed a Co-ordinated Research Programme (CRP) entitled "Activation Cross Sections for the Generation of Long-lived Radionuclides of Importance in Fusion Reactor Technology" with the purpose to obtain reliable information (experimental and evaluated) for 16 long-lived activation reactions of special importance to fusion reactor technology. Participants of 18 laboratories from nine member countries joined in this task.

The germ of ideas for the CRP was born at a meeting in Gaussig, Germany, in 1986. The problem was further discussed at the INDC Meeting in Beijing, 1987. The ideas were fully agreed and the scope of the CRP was established at a follow-up meeting held in Argonne, USA, in 1989. The first Research Co-ordination Meeting (RCM) chaired by E.T. Cheng was held in Vienna in November 1991. In April 1993, the second RCM took place in Del Mar, California, U.S.A. under the chairship of H.K. Vonach. The main purpose of the final CRP meeting, chaired by S.M. Qaim, which was held in St. Petersburg, Russia, from 19 to 23 June 1995, was to prepare the Final Report summarizing the results of the CRP.

The goals of the CRP were completed. By limiting the scope of the CRP to just 16 reactions it was possible to establish a very effective focus to the joint effort of many laboratories that has led to the generation of a set of valuable new data which provide satisfactory answers, or at least partial answers, to several questions of technological concern to fusion. The recommended cross section data for these sixteen reactions can be electronically retrieved by the users from the IAEA Nuclear Data Section online system through INTERNET.

The present report summarizes the final results of the IAEA Co-ordinated Research Programme. The Summary was written by E.T. Cheng and R.A. Forrest. Chapter 1 was prepared by S.M. Qaim, J. Csikai, Y. Ikeda, Lu Hanlin, D.L. Smith and H.K. Vonach, and Chapter 2 was written by M. Blann, A.V. Ignatyuk and G. Reffo. M.B. Chadwick did not participate in the final meeting and sent his contribution for the Final Report to the Scientific Secretary. Chapter 3 describes briefly the evaluated data file resulting from the CRP effort and Chapter 4 includes a list of publications emerging from the CRP.

Vienna, June 1997 — Anatoly B. PASHCHENKO

Summary

At the 1986 IAEA Advisory Group Meeting on Nuclear Data for Fusion Reactor Technology in Gaussig [1] a list of important activation cross sections for fusion reactor materials was presented by E.T. Cheng and adopted by the Advisory Group as high priority data requests for fusion technology. E.T. Cheng pointed out that present design studies required operation at a very low rate of production of long-lived radionuclides in order to reduce the problems of waste disposal and reactor maintenance. In order to meet these requirements, not only all activation cross sections for the fusion materials themselves have to be known, but also those for all possible impurities (practically all elements) if they lead to long-lived ($t_{1/2} \geq 5$ years) radionuclides. This problem was further discussed in more detail by E.T. Cheng in his contribution to the 1987 International Nuclear Data Committee (INDC) Meeting in Beijing [2]. He reported that present estimates of the admissible concentrations of various elements in fusion reactor materials varied by large factors due to insufficient knowledge of the relevant activation cross sections. The situation could be improved since the radionuclides that are probably most important for the radioactive waste problem have been identified.

For these reasons the INDC felt that a Co-ordinated Research Programme (CRP) of the IAEA on the measurement and calculation of these cross sections could make an important contribution to fusion reactor technology and recommended that the Nuclear Data Section of the IAEA start a CRP with the following scope.

The CRP should concentrate on the determination of a relatively small number of important activation cross sections, selecting those reactions, which as yet cannot be estimated reliably from systematics and/or theory and where no reliable measurements exist. The list of these sixteen selected reactions is given in Table 1.

Table 1. Reactions to be considered in the CRP.

$^{27}Al(n,2n)^{26}Al$	$^{159}Tb(n,2n)^{158}Tb$
$^{62}Ni(n,\gamma)^{63}Ni$	$^{158}Dy(n,p)^{158}Tb$
$^{63}Cu(n,p)^{63}Ni$	$^{165}Ho(n,\gamma)^{166m}Ho$
$^{94}Mo(n,p)^{94}Nb$	$^{179}Hf(n,2n)^{178m2}Hf$
$^{98}Mo(n,\gamma)^{99}Mo(\beta^-)^{99}Tc$	$^{182}W(n,n'\alpha)^{178m2}Hf$
$^{109}Ag(n,2n)^{108m}Ag$	$^{187}Re(n,2n)^{186m}Re$
$^{151}Eu(n,2n)^{150m}Eu$	$^{191}Ir(n,\gamma)^{192m2}Ir$
$^{153}Eu(n,2n)^{152g+m2}Eu$	$^{193}Ir(n,2n)^{192m2}Ir$

Following this recommendation, the Nuclear Data Section of the IAEA initiated the requested CRP in 1988 and obtained the participation of 18 laboratories from 9 countries. At the same time other laboratories in China, Japan and the USA, not directly involved in the IAEA project, have been engaged in measurements relevant to the objectives of the CRP. These are shown in Table 2.

Table 2. Participating countries and laboratories.

Country	Number of laboratories	Laboratories
Austria	1	Institut für Radiumforschung und Kernphysik - Vienna
China	4	Institute of Atomic Energy - Beijing, Lanzhou University, Peking University, Sichuan University
Germany	1	Institut für Nuklearchemie, Forschungszentrum - Jülich
Hungary	1	Institute of Experimental Physics - Debrecen
Italy	2	ENEA Centro Richerche Energia, ENEA Nuclear Data Centre - Bologna
Japan	2	Data Engineering - Yokohama, Japan Atomic Energy Research Institute - Tokai
Russia	2	Institute of Physics and Power Engineering - Obninsk, V.G. Khlopin Radium Institute - St. Petersburg
U.K.	2	United Kingdom Atomic Energy Authority, Oxford University
U.S.A.	3	Argonne National Laboratory, Lawrence Livermore National Laboratory, Los Alamos National Laboratory
Total = 9	18	

The IAEA Consultants' Meeting on this subject was held in Argonne, U.S.A., in September 1989 [3] in close co-operation with the NEA-NDC Specialist Meeting on activation cross sections. The first Research Co-ordination Meeting (RCM) chaired by E.T. Cheng was held in Vienna in November 1991 [4]. In April 1993, the second RCM was held under the chairship of H.K. Vonach in Del Mar, California [5], in conjunction with the International Workshop on Nuclear Data for Fusion Reactor Technology. The third and final RCM of this CRP under the chairship of S.M. Qaim was held in St. Petersburg, Russia, in June 1995. The individual publications are listed in references 3-5 and are given in Chapter 3.

Two conference review papers have been presented which summarized progress made in the CRP project. The first of these reports was presented at the 1991 Jülich International Conference on Nuclear Data for Science and Technology [6]. The second was presented at the 1994 Gatlinburg International Conference [7]. The broad scope of the research effort which developed under the auspices of this CRP is well described in these progress reports. In addition to research on the selected reactions in Table 1, progress has been made in the acquisition of new data for additional reactions, in the development of improved experimental techniques, and in the refinement of nuclear models. In the latter context, attention should be called to new insight gained in understanding isomer ratios. Experiments concentrated on particular energy ranges. Capture measurements covered energies < 2 MeV, while most of the remaining reactions were measured at 14 MeV, although a major advance during the course of the CRP has been the new measurements in the 9 - 12 MeV energy range.

Because of great difficulty in obtaining cross section results from direct measurements for many of the reactions in Table 1, it has been necessary to supplement experiments with nuclear modelling and evaluation activities. In the case of the modelling work, excitation functions were determined independently in several laboratories. For threshold reactions these were normalized at 14.5 MeV to evaluated experimental data, where available, or to cross section values estimated from systematics and/or consideration of data for shorter-lived associated processes. The normalized theoretical excitation functions of threshold reactions have been averaged and the resulting hybrid curves used for comparisons with data obtained for a few reactions at energies below 14 MeV.

At the second RCM an additional Working Group was formed to consider the role of charged particle reactions in the production of radioactive inventories for fusion devices. It was recommended to extend the CRP to consider charged particle reactions. In particular it was recommended to determine the impact of sequential charged particle reactions (SCPR) on realistic materials. At the third RCM a paper was presented which considered a wide range of realistic materials (steels, vanadium alloys, breeding materials and multipliers). The conclusion was that if impurities are included then the effects of SCPR are at most about 20% and within the estimated uncertainties of the results without SCPR. This general conclusion needs to be qualified for vanadium alloys and breeding materials (e.g. FLiBe) if very careful control of impurities is possible. The time scale of the most significant effects due to SCPR are typically of a few tens of years, so that for the current CRP which is focused on long-lived radionuclides, this new mechanism can be ignored.

This CRP has produced extensive results relevant to the reactions in Table 1, thereby greatly improving the nuclear data base for fusion energy applications. The status is now reasonably acceptable for 8 of the reactions. However, there are unacceptable uncertainties for the 8 remaining reactions. Poor knowledge of the decay half-life remains a concern for several of these reactions. The experimental status of each reaction is given in Chapter 1. Theoretical work has enabled the excitation function in the relevant energy range to be given (Chapter 2), and by using the evaluated experimental value as a renormalizing value a recommended excitation function for each reaction are available and can be obtained in electronic form from the IAEA Nuclear Data Section.

This CRP has spawned studies in related areas not discussed in this report. These have also contributed significantly to improving our general knowledge of neutron-induced activation processes. Consequently, this CRP can be considered a success.

References

[1] Proceedings of the IAEA Advisory Group Meeting on Nuclear Data for Fusion Reactor Technology, Gaussig, Germany, 1-5 December 1986, Report IAEA-TECDOC-457, IAEA, Vienna, 1988.

[2] Minutes of the 16th INDC Meeting, ed. A.J. Deruytter, Report INDC/(89), IAEA, Vienna, 1989.

[3] Proceedings of an IAEA Consultants' Meeting held at Argonne National Laboratory, Argonne, Illinois, U.S.A., 11-12 September 1989, ed. Wang DaHai, Report INDC(NDS)-232/L, IAEA, Vienna, 1990.

[4] First Meeting of a Co-ordinated Research Programme organized by the IAEA and held in Vienna, 11-12 November 1991, ed. Wang DaHai, Report INDC(NDS)-263, IAEA, Vienna, 1992.

[5] Activation Cross Sections for the Generation of Long-lived Radionuclides of Importance in Fusion Reactor Technology: Report of the Second IAEA Research Co-ordination Meeting held at Del Mar, California, 29-30 April 1993, ed. A.B. Pashchenko, Report INDC(NDS)-286/L (Texts of Papers) and INDC(NDS)-288/L (Summary), IAEA, Vienna, 1993.

[6] H. Vonach, "Report on the IAEA Co-ordinated Research Programme on Activation Cross Sections for the Generation of Long-lived Activities of Importance in Fusion Reactor Technology". Proceedings of an International Conference on Nuclear Data for Science and Technology, Jülich, Germany, 13-17 May 1991, ed. S.M. Qaim, Springer-Verlag, Berlin, 1992, p. 279.

[7] D.L. Smith and A.B. Pashchenko, "Investigation of the Generation of Long-lived Radionuclides of Importance in Fusion Reactor Technology: Report on a Co-ordinated Research Programme Sponsored by the International Atomic Energy Agency". Proceedings of an International Conference on Nuclear Data for Science and Technology, Gatlinburg, Tennessee, U.S.A., 9-13 May 1994, ed. J.K. Dickens, American Nuclear Society, LaGrange Park, Illinois, 1995, p. 859.

Chapter 1

THE EXPERIMENTS PERFORMED UNDER THE AUSPICES OF THE CRP

In this section of the report we address only those cross sections measured specifically in the CRP for the 16 reactions indicated in Table 1. It should be noted that a review of the literature indicates that there exists a data base of prior experimental information for some of the processes considered in the CRP. These data certainly play a role in the evaluation of 14 MeV cross sections presented in this report. Furthermore, there exist auxiliary data sets which, considered in combination with each other or with cross sections based on systematic trends, enable indirect predictions to be made of desired quantities. This supporting information is not duplicated in this report, however this does not lessen in any way their importance to this project.

An important factor in comparing data sets from various laboratories participating in the CRP is to assure that identical nuclear decay parameters are utilized in deducing cross sections from the raw data. The critical parameters are the half life and branching factors for the observed decay radiations. The set of decay data values adopted in the CRP is given in Table 3.

The information generated by the CRP experiments is summarized in two tables: Table 4 gives all the measured cross section values near 14 MeV. Table 5 presents all reported results for lower neutron energies, mainly for region 9-12 MeV for threshold reactions and < 2 MeV for (n,γ) reactions. In those cases where the individual results did not correspond to adopted values of decay data, reported values have been renormalized to be consistent with Table 3 values. General comments on the data for the individual reactions are presented below.

^{27}Al(n,2n)^{26}Al

The only measurement from the CRP comes from JAERI. A few comparable values are available from literature, representing work performed prior to this CRP. The significant problem is that this cross section varies rapidly with the energy near 14 MeV due to a high threshold. Therefore, the cross section determination is extremely sensitive to the energy scale. Recent measurements from 20-40 MeV via the accelerator mass spectrometry (AMS) technique at Tohoku University will be useful in helping to determine the shape of the excitation function. Sample irradiations in the 14 MeV range have taken place at IRK and in a Debrecen/Cologne collaboration. These samples are to be analysed by the AMS so it may be some time before final results are available.

$^{63}Cu(n,p)^{63}Ni$

No cross section values have been measured to date by this CRP. However, two prior values are available near 14 MeV but they differ by more than a factor of two. Copper samples were irradiated at ANL in the Be(d,n) neutron spectrum and in the Jülich/Debrecen collaboration at 14.5 MeV and 7-9 MeV. Termination of the experimental programme at ANL necessitated abandonment of all attempts to count ^{63}Ni activities there. Counting work for Jülich/Debrecen is in progress. These results should be available in late 1996. Finally, some data are available in the literature from experiments that detect protons directly. Care must be taken in these experiments to assure that most of the emitted protons are detected and meaningful comparison is to be made with activation results.

$^{94}Mo(n,p)^{94}Nb$

Two values near 14 MeV have been provided for the CRP. They agree reasonably well with a prior value from the literature. A sample has been irradiated at 14.6 MeV in the Debrecen/Jülich/Cologne collaboration. Yield determination by AMS is pending. Another sample has been irradiated at 14.7 MeV in a JAERI/KRI collaboration. Counting and analysis are in progress. Some concern has been expressed about the impact of $^{95}Mo(n,n'p)^{94}Nb$. This reaction does not contribute significantly when samples enriched in ^{94}Mo are used. Prior work at JAERI indicates that the (n,n'p) contribution is $<20\%$ at 14 MeV for natural molybdenum.

$^{109}Ag(n,2n)^{108m}Ag$

Cross section values near 14 MeV have been provided for the CRP by ANL/JAERI, Beijing, JAERI, KRI, Debrecen and Lanzhou University. These data are in reasonably good agreement. In addition, data are available in the 10-12 MeV range from Beijing and Jülich/Debrecen. The latter work utilized ^{109}Ag enriched samples. These results are in reasonable agreement. Data acquired at ANL have been rejected because of contamination by the $^{107}Ag(n,\gamma)^{108m}Ag$ reaction in the natural samples.

$^{179}Hf(n,2n)^{178m2}Hf$

Data have been provided to the CRP at 14 MeV by JAERI, JAERI/ANL, Beijing, Lanzhou University and Harwell. These results are in reasonable agreement. Furthermore, Beijing has made a measurement at 9.9 MeV using a natural Hf sample. However, interpretation of this lower-energy point is complicated by the presence of a significant $^{178}Hf(n,n')^{178m2}Hf$ component.

$^{182}W(n,n'a)^{178m2}Hf$

Cross section values have been provided to the CRP by JAERI, Lanzhou University and KRI near 14 MeV. Considering their large errors they are in reasonably good agreement. Concern exists for possible contamination by $^{179}Hf(n,2n)^{178m2}Hf$ due to Hf impurities in the W samples. However, if the purity of W is 99.9% or greater then the influence of Hf should be negligible. The investigation carried out at KRI using reactor neutrons showed that the possible contamination of Hf in tungsten samples used for $^{182}W(n,n'\alpha)^{178m2}Hf$ cross section determination in KRI does not exceed 10^{-6} atom/atom.

$^{151}Eu(n,2n)^{150m}Eu$ (36.9 year state only)

Data near 14 MeV have been provided for the CRP by JAERI/ANL, Beijing, Lanzhou University, JAERI and KRI. The presently available data agree reasonably well in this energy range. In addition, data are available in the 9-12 MeV range from Jülich/Debrecen and Beijing. They agree reasonably well. Data will also be provided later from ANL/LANL once corrections are determined for effects of the neutron spectrum.

$^{153}Eu(n,2n)^{152g}Eu$

Data near 14 MeV have been provided for the CRP by JAERI, Beijing and KRI. No results were obtained from ANL/JAERI because contamination from $^{151}Eu(n,\gamma)^{152g}Eu$ was large and difficult to predict accurately for natural Eu. An attempt to analyse data from ANL/LANL near 10 MeV and for Be(d,n) spectrum was also abandoned for the same reason.

$^{159}Tb(n,2n)^{158}Tb$

Reasonably consistent data near 14 MeV have been provided for the CRP by ANL/JAERI, Beijing, Lanzhou University and JAERI. Cross section values have also been obtained for 9-11 MeV by Jülich/Debrecen and Beijing. A value near 10 MeV will be available from ANL/LANL after a correction is made for the neutron spectrum.

$^{158}Dy(n,p)^{158}Tb$

No data were provided by the CRP. This is a very difficult case for experimental work. The contribution of this reaction in a fusion reactor would probably be dominated by the $^{159}Tb(n,2n)^{158}Tb$ yield due to a larger cross section and higher target isotopic abundance.

$^{193}Ir(n,2n)^{192m2}Ir$

Values were provided to the CRP by JAERI and Beijing near 14 MeV. They agree within the errors.

$^{191}Ir(n,\gamma)^{192m2}Ir$

No data were obtained by the CRP. A measurement at thermal neutron energy has been made by Beijing, but the sample is still cooling. The relative importance of this reaction and $^{193}Ir(n,2n)^{192m2}Ir$ remains to be determined. It depends strongly on the assumed fusion-reactor neutron spectrum.

$^{187}Re(n,2n)^{186m}Re$

Values have been provided to the CRP by JAERI and Beijing near 14 MeV. They agree within the range of relatively large errors. KRI and Debrecen have irradiated a Re sample at 14 MeV but a longer cooling time is needed prior to counting the ^{186m}Re activity.

$^{62}Ni(n,\gamma)^{63}Ni$

No data were obtained by the CRP. It is noted that a value for thermal neutrons has been obtained from a fission reactor measurement at Jülich. The importance of this reaction to fusion depends strongly on whether Ni is eventually used as a structural components material in fusion reactors.

$^{98}Mo(n,\gamma)^{99}Mo(\beta^-)^{99}Tc$

Data have been provided to the CRP by the Sichuan University for the 29-1100 keV energy range. The presently available values (from the Jülich Conference) have been revised recently to account for a change in the fluence standard. Data from KRI are also available and these are reported at the St. Petersburg RCM. The energy range is 700-2000 keV. These two data sets are mutually consistent.

$^{165}Ho(n,\gamma)^{166m}Ho$

The only data reported to the CRP are three values from the Sichuen University, at 203, 676, 974 keV. This cross section can be estimated indirectly from σ_{tot}-$\sigma_{n\gamma}$ using data available in the literature for these processes.

Table 3. Decay data adopted within the CRP

Activation Product	Half-life (years)	E_γ (keV)	I_γ (%)
^{26}Al	$7.16\pm0.32)\cdot10^5$	1808.65	99.76 ± 0.04
^{63}Ni	100 ± 2	no gamma	β^-, 100%
^{94}Nb	$(2.03\pm0.16)\cdot10^4$	702.63	98 ± 2
		871.10	100
^{99}Mo	65.94 ± 0.01	140.5	89.4 ± 0.02
^{108m}Ag	433 ± 15	434.0	90.5 ± 0.9
^{150m}Eu	36.9 ± 0.9	334	96 ± 3
		439.4	80.35 ± 3
$^{152g+m2}Eu$	13.56 ± 0.03	121.78	28.37 ± 0.13
		344.28	26.57 ± 0.11
		778.90	12.97 ± 0.06
		964.13	14.63 ± 0.06
		1408.01	20.85 ± 0.09
^{158}Tb	180 ± 11	944	43.9 ± 1.3
		184.4	72.6 ± 0.9
^{166m}Ho	$(1.2\pm0.18)\cdot10^3$	711.7	55.3 ± 0.65
		810.3	58.1 ± 0.68
$^{178m2}Hf$	31 ± 1	325.56	94.1 ± 0.3
		574	83.8
		495	68.9
^{186m}Re	$(2.0\pm0.5)\cdot10^5$	137*	8.22 ± 0.25
$^{192m2}Ir$	241 ± 9	316**	82.8 ± 0.4
		155.16	0.00097

* from subsequent decay of ^{186g}Re
** from subsequent decay of ^{192g}Ir

Table 4. Cross Section Measurements*) within the CRP around E_n = 14 MeV

Reaction	En(MeV)	Cross Section (mb)	Laboratory
$^{27}Al(n,2n)^{26}Al$	14.1	19±10	JAERI 95
	14.5	14.5±7	
	14.1	14.8±5	
$^{63}Cu(n,p)^{63}Ni$	14.6	70±13	Jülich/ Debrecen
$^{94}Mo(n,p)^{94}Nb$	14.1	58±9	JAERI 95
	14.8	54±12	
	14.1	44±18	JAERI 91
	14.5	48±20	
	14.8	58±17	
$^{109}Ag(n,2n)^{108m}Ag$	13.7	634±39	KRI 95
	14.1	682±40	
	14.5	695±40	
	14.9	709±41	
	14.1	578±27	JAERI 95
	14.5	643±30	
	14.8	671±31	
	14.7	651±44	ANL/JAERI
	14.7	706±51	
	14.5	677±82	Debrecen
	14.5	716±44	Debrecen
	14.19	763±21	CIAE 95
	14.28	732±39	
	14.44	760±35	
	14.77	784±25	
	14.83	795±25	
	13.64	759±24	Lanzhou Univ.
	13.79	759±61	

Reaction	En(MeV)	Cross Section (mb)	Laboratory
	14.03	774±66	
	14.33	763±27	
	14.5	697±60	Jülich/ Debrecen
	14.60	790±27	
	14.80	805±24	
$^{151}Eu(n,2n)^{150m}Eu$	14.19	1234±28	CIAE 95
	14.44	1260±37	
	14.77	1264±29	
	13.72	1283±50	Lanzhou Univ.
	14.35	1208±46	
	14.68	1211±46	
	14.80	1213±46	
	13.52	1169±68	KRI 95
	13.75	1210±65	
	13.98	1181±67	
	14.21	1132±69	
	14.44	1169±62	
	14.67	1182±59	
	14.90	1263±58	
	14.70	1259±97	ANL/JAERI
	14.70	1305±90	
	14.10	1260±54	JAERI 95
	14.50	1213±61	
	14.80	1323±66	
$^{153}Eu(n,2n)^{152g+m2}Eu$	14.10	1326±75	JAERI 95
	14.50	1533±77	
	14.80	1326±75	
	13.52	1464±54	KRI 95
	13.57	1515±59	
	13.98	1516±53	

Reaction	En(MeV)	Cross Section (mb)	Laboratory
	14.21	1500±61	
	14.44	1445±52	
	14.67	1545±49	
	14.90	1460±44	
	13.70	1580±120	KRI 90
	14.10	1659±130	
	14.50	1480±114	
	14.90	1514±116	
	14.77	1560±70	CIAE 95
$^{159}Tb(n,2n)^{158}Tb$	14.7	1981±184	ANL/JAERI
	14.7	2072±178	
	13.72	2077±277	Lanzhou Univ.
	14.35	2144±112	
	14.60	1909±85	
	14.80	1922±89	
	14.19	1980±56	CIAE
	14.77	1968±58	
	14.1	1937±82	JAERI 95
	14.7	1932±82	
	14.9	1944±83	ANL/JAERI
$^{179}Hf(n,2n)^{178m2}Hf$	14.8	6.75±.80	HARWELL
	14.1	5.8±.4	JAERI
	14.8	6.8±.4	
	14.8	6.3±.6	
	14.7	7.2±.7	ANL/JAERI
	14.19	6.6±.6	CIAE
	14.77	7.0±.6	CIAE
	14.60	6.04±.32	Lanzhou Univ.
$^{182}W(n,n'\alpha)^{178m2}Hf$	14.90	.010±.006	KRI
	14.80	.026±.013	JAERI
	14.80	.016±.010	CIAE

Reaction	En(MeV)	Cross Section (mb)	Laboratory
	14.80	.014±.008	JAERI
$^{187}Re(n,2n)^{186m}Re$	14.80	541±189	JAERI
	14.77	340±192	CIAE
$^{193}Ir(n,2n)^{192m2}Ir$	14.80	147±52	JAERI
	14.19	167±24	CIAE

*) For References see Chapter 3. The data of the same energy values from the same laboratories refer to independent measurements.

Table 5: Cross Section measurements within the CRP below E_n = 14 MeV

Reaction	E_n^* (MeV)	Cross Section (mb)	Laboratory
$^{63}Cu(n,p)^{63}Ni$	7.2±0.4	91 ± 23	Jülich/Debrecen 95
	8.2±0.4	105 ± 15	Jülich/Debrecen 95
	9.2±0.4	112 ± 29	Jülich/Debrecen 95
$^{98}Mo(n,\gamma)^{99}Mo$	0.029	74.2 ± 6.4	SU/CIAE 95
	0.059	43.6 ± 3.8	SU/CIAE 95
	0.121	33.8 ± 2.9	SU/CIAE 95
	0.196	29.8 ± 2.6	SU/CIAE 95
	0.215	30.6 ± 2.6	SU/CIAE 95
	0.230	29.4 ± 2.5	SU/CIAE 95
	0.376	28.2 ± 2.4	SU/CIAE 95
	0.655	30.1 ± 2.1	SU/CIAE 95
	0.962	20.2 ± 1.5	SU/CIAE 95
	1.10	16.3 ± 1.2	SU/CIAE 95
	0.74	32 ± 2	KRI 95
	1.26	12 ± 1	KRI 95
	1.46	14 ± 1	KRI 95
	1.76	13 ± 1	KRI 95
	1.97	9 ± 1	KRI 95
$^{109}Ag(n,2n)^{108m}Ag$	9.9	45.1 ± 4.1	CIAE 95
	10.86 ± 0.27	276 ± 36	Jülich/Debrecen 95
	12.17 ± 0.30	451 ± 58	Jülich/Debrecen 95
$^{151}Eu(n,2n)^{150m}Eu$	9.18 ± 0.24	164 ± 23	Jülich/Debrecen 95
	9.60 ± 0.24	250 ± 28	Jülich/Debrecen 95
	10.10 ± 0.24	335 ± 32	Jülich/Debrecen 95
	10.83 ± 0.30	849 ± 102	Jülich/Debrecen 95
	11.20 ± 0.30	952 ± 142	Jülich/Debrecen 95
	12.14 ± 0.30	982 ± 127	Jülich/Debrecen 95
	10.0 ± 0.20	282 ± 32	ANL/JAERI 95
	9.5	307 ± 35	CIAE 95
	9.9	496 ± 40	CIAE 95
$^{159}Tb(n,2n)^{158}Tb$	9.18 ± 0.24	333 ± 32	Jülich/Debrecen 95
	9.60 ± 0.24	547 ± 60	Jülich/Debrecen 95
	10.10 ± 0.24	828 ± 99	Jülich/Debrecen 95
	10.0 ± 0.20	555 ± 77	ANL/JAERI 95
	10.83 ± 0.30	1410 ± 140	Jülich/Debrecen 95
	9.5	491 ± 61	CIAE 95
	9.9	803 ± 76	CIAE 95
$^{165}Ho(n,\gamma)^{166m}Ho$	0.203	37.4 ± 5.6	SU/CIAE 95
	0.676	12.1 ± 2.4	SU/CIAE 95
	0.974	10.9 ± 3.1	SU/CIAE 95
$^{179}Hf(n,2n)^{178m2}Hf$	9.9	0.32 ± 0.09	CIAE 95

* given uncertainties refer to value of the mean neutron energy

Chapter 2

THEORY AND SYSTEMATICS

This CRP integrated nuclear modelling and judicious use of systematics with experimental measurements and evaluation procedures in order to provide final evaluated files for 16 reactions of interest for fusion activation analysis. Nuclear modelling is most reliable in predicting major reaction channels, such as (n,xn), for which the cross sections form a large part of the total reaction cross section, and should have greatest uncertainties in predicting very small cross sections. Theory may be expected to give the correct reaction thresholds and give good peak positions for the excitation functions. Shapes are also generally well reproduced. Peak cross-sections, especially for minor channels, are less reliable. With these broad comments we consider the interaction of experiment, evaluation and theory for this CRP and resulting recommendations.

An evaluation of the experimental data for 14.5 MeV neutron induced reactions was performed by Vonach and Wagner [1] for the reactions under consideration by this CRP. Theoretical results were presented for these reactions by several groups. All calculations were Hauser-Feshbach, preceded by precompound models, and all used known low-lying level structure as input. Chadwick and Ignatyuk normalized all calculations to the evaluated results of [1] at 14.5 MeV incident neutron energy and then presented averaged calculated excitation functions [2]. Results of these calculations were presented at the Gatlinburg Conference for the ^{94}Mo(n,p)$^{94m+g}$Nb, ^{109}Ag(n,2n)^{108m}Ag, ^{151}Eu(n,2n)^{150m}Eu, ^{187}Re(n,2n)^{186m}Re, ^{153}Eu(n,2n)^{152m2}Eu, ^{179}Hf(n,2n)^{178m2}Hf, ^{159}Tb(n,2n)^{158}Tb and ^{193}Ir(n,2n)^{192m}Ir reactions [3]. We recommend*) renormalization of these curves to the new evaluated experimental data which will be prepared by Vonach (see INDC(NDS)-342, 1996, p.99) taking into account the results presented at the St. Petersburg RCM. Chadwick and Ignatyuk should prepare the revised extrapolations of the averaged theoretical curves up to 20 MeV.

New experimental cross sections were reported at the final RCM by Qaim et. al. and Lu Hanlin et. al. for the ^{109}Ag(n,2n)^{108m}Ag, ^{151}Eu(n,2n)^{150m}Eu and ^{159}Tb(n,2n)^{158}Tb reactions in the energy region of 9.5 to 12.5 MeV. Furthermore, the older experimental data by Qaim et. al. for the ^{151}Eu(n,2n)^{150m}Eu and ^{159}Tb(n,2n)^{158}Tb reactions in the energy region of 9.2 to 10.1 MeV [3,4] were revised. The experimental results of Weixiang et. al. and the new measurements of Qaim et. al. are in agreement with the calculated excitation functions, while the revised results of Qaim et. al. are still 20 to 40% below the calculated excitation functions for ^{151}Eu(n,2n)^{150m}Eu. We recommend that the normalized averaged theoretical curves be adopted for the final evaluated file for energies up to 20 MeV for ^{109}Ag(n,2n)^{108m}Ag and ^{159}Tb(n,2n)^{158}Tb, and that the theoretical curve for the ^{151}Eu(n,2n)^{150m}Eu reaction be adopted after adjustment of the low energy region to the experimental results.

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*) This was written at the final CRP meeting in St. Petersburg. The final evaluated data file resulting from the CRP (see Chapter 3) was prepared in accordance with recommendations of the final meeting and was released in 1996.

The theoretical excitation functions for the (n,p) reactions on ^{63}Cu and ^{94}Mo are in reasonable agreement with the experimental results reported for neutron energies around 14.7 MeV. In the absence of lower energy experimental data we recommend that the calculated excitation functions be used to determine the final evaluated files. In the case of the $^{63}Cu(n,p)$ reaction Manokhin has shown that the phenomenological systematics based on $^{65}Cu(n,p)$ are also a very useful tool in evaluation, giving experimentally based justification for the excitation function trend below 14 MeV. A new empirical estimation 70 ± 9mb for the $^{63}Cu(n,p)$ cross section at 14.5 MeV, reported at this meeting by Csikai, is very close to the Obninsk theoretical value giving confidence in the latter to ultimately guide the evaluation. However, the final evaluation should await the experimental results on this reaction at energies of 7 - 10 and 14.7 MeV which are expected from the Jülich/Debrecen group by the end of 1995. Regarding the $^{158}Dy(n,p)$ reaction, the new JAERI result 10 - 20 mb at 14.5 MeV is in reasonable agreement with theory, although the experimental uncertainties are large. The empirical estimation 10.6 ± 1.2 mb proposed by Csikai and based on experimental data for other Dysprosium isotopes gives a value that agrees surprisingly well with the Obninsk theoretical curve. The theoretical curve should therefore be recommended for the final file.

The threshold of the $^{27}Al(n,2n)$ reaction is close to 14 MeV. Therefore the experimental data points near 14 MeV do little to establish the maximum of the excitation function. The $^{27}Al(n,2n)$ excitation function has been calculated by the Obninsk group and Reffo has provided the ENEA calculated file. The Obninsk group has also calculated the isomer ratio for the $^{26m,g}Al$ production. We propose acceptance of the Obninsk results connected smoothly with the averaged experimental data in the near threshold region as the recommended evaluation. The evaluations for the near threshold region should be performed by Vonach.

New experimental data for the $^{98}Mo(n,\gamma)$ reaction presented at the St. Petersburg RCM help to confirm the evaluations included in the JEF-2.2 general purpose files. There are no new results for the $^{62}Ni(n,\gamma)$ reaction. We recommend acceptance of the JEF-2.2 and EFF-2.4 evaluations for both reactions, respectively.

The $^{179}Hf(n,2n)^{178m2}Hf$ isomer production cross section will be subject to the greatest uncertainty because of the very small (6 mb) cross section at 14 MeV, and because calculations of isomer ratios require more challenging physical models than do calculations of excitation functions of nuclides for which all levels deexcite promptly to ground state. More work is required to scrutinize theory for isomer production and we feel that it would be wise for Ignatyuk to spend several days at LLNL just before or after the December Del Mar Meeting working further on this topic with Chadwick in order to prepare the final recommended data file. This work should also include the preparation of the final recommended files for the $^{165}Ho(n,\gamma)^{166m}Ho$ and $^{191}Ir(n,\gamma)^{192m}Ir$ reaction cross sections[**)]. We expect that this collaboration will be further strengthened by the participation of the Bologna Nuclear Data Center. The final recommended files for all reactions included in the CRP should be prepared at Obninsk in the framework of this collaboration and be made available to the IAEA Nuclear Data Section for wide distribution to member countries.

**) The ECN evaluations by J. Kopecky et.al. were adopted for the final recommended data for both reactions

Special discussion was focused on the $^{182}W(n,n'\alpha)^{178m2}Hf$ reaction evaluations. The Obninsk group carefully analyzed calculations of (n,α) reaction cross sections and modified their codes to include the fast (direct+precompound) emission of alpha-particles. They benchmarked calculations against experimental data available for heavy nuclei. Therefore we would expect reasonable predictive power for the total cross sections of (n,α) and $(n,n'\alpha)$ reactions. On the basis of calculated isomer ratios and the experimental value of the isomer ratio for the $^{179}Hf(n,2n)^{178m2}Hf$ reaction, we would estimate the $^{182}W(n,n'\alpha)$ $^{178m2}Hf$ cross section at 14.5 MeV at around $\sim 10^{-4}$ - 10^{-5} mb. The experimental estimations for this cross section are in reasonable mutual agreement, but two orders of magnitude higher. At present it is difficult to understand such a difference. As this reaction is of less importance than originally projected, we recommend use of the Obninsk calculations normalized to the averaged experimental data as the upper limit for the $^{182}W(n,n'\alpha)$ reaction cross section.

It is necessary to remark that the selection of theoretical models for cluster emission reactions requires further scrutiny. A benchmarking has been sparse to nonexistent. This is an area needing further attention and development in order to be confident that we have satisfactory models when needs arise for data of this type.

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2. M.B. Chadwick et. al., Ibid., p. 123.
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Chapter 3

DATA RECOMMENDED BY THE CRP

The complete set of recommended excitation functions for sixteen reactions was prepared by A.V. Ignatyuk in co-operation with M.B. Chadwick, as discussed in Chapter 2.

For reactions, where the CRP produced cross section data for one of the partial channel, the CRP results have been complemented with recommended data for all other channels.

Availability

The evaluated cross section data library for activation reactions that resulted from the CRP effort are available online through the IAEA Nuclear Data Section FTP service.

Commands to be used:

- ftp iaeand.iaea.or.at
- user ndsopen
- cd [IRDL.LLCRP]
- get DATA_FILE.CRP
- exit

Format

The format of the DATA_FILE.CRP file is essentially that of the MF=3 file of ENDF-5 format with the following deviations (the resulting format is usually referred to as the FENDL/A or EAF format):

(1) Two comment lines are used stating the origin of data, revisions and information about renormalizations.
(2) The material number MAT consists of Z and two last digits of A.
(3) The identifier LFS is used to indicate the (isomeric) states of the final nucleus. Here the convention was adopted that LFS = 99 means total production cross-section; LFS = i means production of ground state (i = 0), m1 (i = 1) and m2 (i = 2), respectively. The reaction nomenclature is that of ENDF format, except that reaction numbers leading to metastable states have been increased by 300 or 600 (for m1 and m2, respectively). The cross sections for one material number are ordered according to increasing MT numbers, except that cross sections leading to metastable states follow immediately after the cross section leading to the ground state.

The reaction to the ground state is given first, followed by reactions to the metastable states (if any).

Chapter 4

LIST OF PUBLICATIONS EMERGING FROM THE CRP

Agreement No. 4882/CF

Chief Scientific Investigator: G. J. Csikai
Institute of Experimental Physics, Debrecen, Hungary

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Agreement No. 5060/CF

Chief Scientific Investigator:
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Agreement No. 5061/CF

Chief Scientific Investigator:
S.M. Qaim, Forschungszentrum Jülich GmbH, Jülich, Germany

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Agreement No. 5062/CF

Chief Scientific Investigator:
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Chief Scientific Investigator:
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Agreement No. 5677/CF

Chief Scientific Investigator:
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Agreement No. 6242/CF

Chief Scientific Investigator:
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Agreement No. 6719/CF

Chief Scientific Investigator:
A.V. Ignatyuk, Institute of Physics and Power Engineering, Obninsk, Russia

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Attachment

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