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INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

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

Summary Report of the Second IAEA Research Coordination Meeting
hosted by
TSI Research, Del Mar, California, USA
29 to 30 April 1993

Edited by A.B. Pashchenko
IAEA Nuclear Data Section
Vienna, Austria

November 1993

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

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ABSTRACT

The present report contains the Summary of the Second IAEA Research Co-ordination Meeting (RCM) on "Activation Cross Sections for the Generation of Long-Lived Radionuclides of Importance in Fusion Reactor Technology" which was hosted by TSI Research at Del Mar near San Diego and held from 29 to 30 April 1993. This RCM was organized by the IAEA Nuclear Data Section (NDS), with the cooperation and assistance of local organizers from TSI Research and Westinghouse Hanford Company.

The papers prepared and presented by the participants at the meeting has been published as separate report **INDC(NDS)-286/L**.

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Attachments

Second IAEA Research Co-ordination Meeting on "Activation Cross Sections for the Generation of Long-Lived Radionuclides of Importance in Fusion Reactor Technology", 29-30 April 1993, Del Mar, California, U.S.A.

(1) Introduction

The second Research Co-ordination Meeting (RCM) of the Agency's Co-ordinated Research Programme (CRP) on "Activation Cross Sections for the Generation of Long-Lived Radionuclides of Importance in Fusion Reactor Technology" was organized by the IAEA Nuclear Data Section (NDS) with co-operation and assistance of local organizers from TSI Research (Dr. E.T. Cheng) and Westinghouse Hanford Company (Dr. F.M. Mann) and held at Del Mar near San Diego, California, U.S.A., from 29 to 30 April 1993.

The purpose of this meeting was to discuss and evaluate the results of the researches carried out by each participating laboratory under this CRP and to review the status and remaining gaps in the required cross sections for those well-defined activation reactions leading to long-lived radionuclides supposed to be of most importance for radioactive waste disposal and material recycling for fusion reactor materials and, if necessary, to identify further measurements and calculations needed to fill these gaps.

The CRP was started in 1992, and the first Research Coordination Meeting of the CRP was held at the IAEA Headquarters, Vienna, from 11 to 12 November 1992. It has 10 participating institutes from Austria, China, Germany, Hungary, Italy, Russia, United Kingdom and USA. The CRP is expected to be finished after a third RCM in 1995.

(2) Organization of the Meeting

The CRP Meeting was convened in conjunction with the International Workshop on Nuclear Data for Fusion Reactor Technology which was also held in co-operation with the Agency at the same place in the following week, from 3 to 6 May 1993, in order to maximize the interactions between the data developers and users.

The RCM was chaired by Professor H.K. Vonach, and Dr. A.B. Pashchenko acted as the IAEA Scientific Secretary.

The Meeting was attended by 35 scientists from 13 Member States. The meeting agenda, the list of CRP participants and the list of attendees are attached to the summary report as Attachments 1, 2 and 3, respectively.

(3) Meeting Proceedings

The Meeting was opened by Dr. E.T. Cheng from TSI Research. Then the IAEA Scientific Secretary for the Meeting, after welcome address, briefly emphasized the scope and goals of the CRP and objectives of the Meeting.

At the first two sessions of the Meeting (Participants' Reports on Measurements and Theoretical Calculations and Evaluations) each research agreement/contract holder made presentations on the work currently being

carried out under the CRP. Each presentation was followed by extensive and occasionally rather intensive discussions.

At the next session of the RCM the participants discussed activation cross section data needs for fission and fusion reactor technology. Dr. E.T. Cheng presented a very interesting report on "Nuclear Data Needs for Fusion Waste Management". Conributions presented by Dr. P. Oblozinsky, Bratislava, Slovak Republik, and Dr. B.Ya. Guzhovskij, Arzamas, Russia emphasized an important role of charged particle reactions on the production of radioactive inventories in fusion reactor materials.

After these presentations and acccompanying discussions, the RCM participants split in three Working Groups for more detailed discussions and for the preparation of extended summary reports. The following Working Groups were formed:

I. Working Group on Experimental Measurements
(Chairman: Prof. Dr. J. Csikai).

II. Working Group on Cross Section Calculations
(Chairman: Dr. M.B. Chadwick).

III. Working Group on Charged Particle Reactions
(Chairman: Dr. P. Oblozinsky).

(4) Conclusions and Recommendations

The main objectives of the second CRP Meeting have been achieved to a large extent and as a result of the discussions, the next steps in the work programme under the CRP have been worked out.

The detailed conclusions and recommendations of the three working groups that were formed during the Meeting are presented in Attachment 4.

(5) Time and Place of the Next Meeting

It was unanimously proposed to have the next CRP-meeting in Russia (either St. Petersburg or Obninsk) in Summer 1995, as two more years are needed for completion of some of the ongoing measurements which still require cooling times of more than one year. It was further agreed to have an informal meeting of the CRP members on the occasion of the 1994 Nuclear Data Conference in Gatlinburg.

(6) Acknowledgement

The CRP meeting participants wish to thank the Agency for focussing much needed attention on the important problems discussed here and wish to thank the staff of TSI Research for the warm hospitality and valuable assistance in conducting the meeting.

ATTACHMENT 1

INTERNATIONAL ATOMIC ENERGY AGENCY

The Second Research Co-ordination Meeting

on

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

Del Mar, California, U.S.A.

29 to 30 April 1993

AGENDA

Thursday, 29 April

a.m. 08:30 — Opening of the RCM

Opening Remarks: E.T. Cheng, TSI Research
A.B. Pashchenko, IAEA

Election of the Chairman
Adoption of the Agenda

a.m. 08:50 — Session 1.
Progress Reports by CRP Participants on Measurements.

(1) Prof. Dr. J. Csikai, Debrecen, Hungary: A. Grallert, J. Csikai, S.M. Qaim, S. Sudár: "Some results on the production of long-lived radionuclides in fast neutron induced reactions".

(2) Dr. D.L. Smith, Argonne, U.S.A.: J. Meadows, D. Smith, R. Haight, Y. Ikeda and C. Konno: " Results from the Argonne, Los Alamos, JAERI Collaboration".

(3) Dr. Y. Ikeda, JAERI, Japan (observer): "Recent measurements on the cross sections for $^{94}Mo(n,p)$&$^{95}Mo(n,np)^{94}Nb$, $^{158}Dy(n,p)^{158}Tb$, $^{187}Re(n,2n)^{186m}Re$, and $^{182}W(n,n\alpha)^{178m2}Hf$ reactions at 14 MeV".

(4) Dr. R.A. Forrest, Harwell, United Kingdom: "Measurements of 14 MeV neutron cross-sections for the production of isomeric states in hafnium isotopes".

a.m. 10:30 — Coffee break

a.m. 10:50

(5) Dr. S.M. Qaim, Jülich, Germany:
"Radiochemical studies of some long-lived soft β^- emitting radioisotopes formed in fast neutron induced reactions".

(6) Dr. LU Hanlin, Beijing, China:
(a) "Measurement of cross sections for the reactions 137-Ba(n,p)Cs-137, 182-W(n,n'a)Hf-178m2 and 193-Ir(n,2n)Ir-192m2 at 14 MeV".
(b) "Cross section measurement for 108-Cd(n,p)Ag-108m reaction".

(7) Dr. M.V. Blinov, St. Petersburg, Russia:
M.V. Blinov, A.A. Filatenkov, S.V. Chuvaev:
"Measurements of some activation cross sections for generation of long-lived nuclides".

a.m. 11:50 Discussion on technical problems with measurements.

p.m. 01:00 Lunch break

p.m. 02:00 <u>Session 2.</u>
Progress reports by CRP participants on theoretical calculations and evaluations.

(1) Prof. Dr. H.K. Vonach, Vienna, Austria:
"Evaluation of the 14 MeV cross-sections for the reactions $^{94}Mo(n,p)^{94}Nb$, $^{109}Ag(n,2n)^{108m}Ag$, $^{151}Eu(n,2n)^{150m}Eu$, $^{153}Eu(n,2n)^{152g+m2}Eu$, $^{159}Tb(n,2n)^{158}Tb$ and $^{179}Hf(n,2n)^{178m}Hf$".

(2) Dr. M.B. Chadwick, Oxford, United Kingdom:
"Application of the Feshbach-Kerman-Koonin preequilibrium theory and Hauser-Feshbach theory (FKK-GNASH codes) to isomer production calculations".

(3) Dr. A.V. Ignatyuk, Obninsk, Russia:
O.T. Grudzevich, A.V. Ignatyuk,
A.B. Pashchenko, A.V. Zelenetsky:
(a) "Consistent calculations of isomer excitation functions in neutron reactions".
(b) "Difference of transmutation cross sections for ground and isomer states".

p.m. 3:30 Coffee break

p.m. 3:45 (4) Prof. Dr. J. Csikai, Debrecen, Hungary:
J. Csikai, A. Grallert, Cs.M. Buczkó,
S. Sudár: "Investigations on the systematics in (n,α) cross sections at 14.5 MeV".

p.m. 04:30 Discussion on predictive power of calculational methods and status of evaluated data.

Friday, 30 April

a.m. 08:30 Session 3.
Activation cross section data needs for fission and fusion reactor technology.

(1) Dr. P. Oblozinsky, Bratislava, Slovakia (observer):
"Influence of sequential (x,n) reactions on production of long-lived radionuclides in fusion reactors".

(2) Dr. B.Ya. Guzhovskij, Arzamas, Russia (observer):
"Review of the activation data for fast charged particle induced reactions".

(3) Dr. E.T. Cheng, Solana Beach, California, U.S.A. (observer):
"Nuclear data needs for fusion waste management".

a.m. 09:50 Coffee break

a.m. 10:15 Session 4.
General discussion on the future scope of the CRP. Organization of working groups to draft the report of the RCM. Drafting of Meeting Conclusions.

Completion of the RCM Working Group Reports.

p.m. 01:00 Lunch break

p.m. 02:00 FINAL CONSIDERATIONS
Discussion of Conclusions and Recommendations.
Drafting of the RCM Conclusions and Recommendations.
Corrections and Adoption of the Final Report.
Adoption of Schedule for Work and Future Meetings.
Closing of the RCM.

ATTACHMENT 2

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Conclusions and Recommendations

The conclusions and recommendations of the meeting were formulated in three working groups, thereafter discussed and unanimously adopted by all CRP participants. In the following they are given in the form of three working group reports.

A. WORKING GROUP ON EXPERIMENTAL MEASUREMENTS

Chairman: J. Csikai (KLTE, Debrecen)

Members: S. Ganesan (IAEA, Vienna)
M. Blinov (KRI, St. Petersburg) †
D.L. Smith (ANL, Argonne)
H. Vonach (IRK, Vienna)
Lu Hanlin (IAE, Beijing)
W. Mannhart (PTB, Braunschweig)
R.C. Haight (LANL, Los Alamos)
A.J. Deruytter (IRMM, Geel)
E. Wattecamps (IRMM, Geel)
S.M. Qaim (KFA, Jülich)
Y. Ikeda (JAERI, Tokai-mura)

(1) **Status of cross sections** measured under the CRP. Status of measurements was summarized by Vonach and is given in Tables 1, 2 and 3 (14 MeV region and lower energy data). These tables, which contain the data available prior to the 2nd RCM, will have to be updated with the data presented at this RCM.

Considerable progress has been achieved since the last meeting held in Vienna in 1991.

(a) Preliminary*) evaluated 14 MeV values were presented by Vonach and are given in Table 1. The cross section values for the $^{151}Eu(n,2n)^{150m}Eu$ and $^{159}Tb(n,2n)^{158}Tb$ reactions at 10 MeV and lower energies reported from ANL and Jülich/Debrecen appear to be lower than those from nuclear model calculations.

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* A number of new measurements of these cross sections were reported at the second RCM at Del Mar and some cross section values presented earlier at the first RCM were slightly revised. Accordingly, the evaluation was updated after this meeting and in its present form contains also all information presented at the Del Mar meeting. Final results of the evaluation will be published in Proceedings of the meeting, INDC(NDS)-286/L, in the paper by H. Vonach and M. Wagner entitled: "Evaluation of some activation cross sections for formation of long-lived activities important for fusion technology".

Table 1

14 MeV Cross Sections (mb)

	$^{63}Cu(n,p)^{63}Ni$	$^{94}Mo(n,p)^{94}Nb$	$^{109}Ag(n,2n)^{108m+}Ag$	$^{151}Eu(n,2n)^{150m}Eu$	$^{153}Eu(n,2n)^{152m}Eu$	$^{159}Tb(n,2n)^{159}Tb$
IRK-89 Evaluation			689 ± 73	1325 ± 94	1442 ± 60	1930 ± 49
Debrecen	Measurement in progress	Measurement in progress	677 ± 82 716 ± 44			
JAERI/ANL "			694 ± 32 682 ± 46	1257 ± 73 1258 ± 52		2037 ± 160 2072 ± 190
Beijing			753 ± 23	1219 ± 28	1544 ± 42	1968 ± 56
JAERI		50 ± 18 56 ± 11	723 ± 35	1220 ± 58	1506 ± 78	
St. Petersburg		Measurement in progress	709 ± 122	1090 ± 84 1142 ± 60	~ 1580 ± 110 1492 ± 50	
ANL (Greenwood)	54 ± 4	50.1 ± 5.3				
Jülich	~ 120 (new measurement in progress)					
Lanzhon University			773 ± 30			

IRK-89 Evaluation			< 100	184 ± 44	592 ± 122
Debrecen					
JAERI/ANL	7.2 ± 0.56				
JAERI	6.3 ± .6	.014 ± .008 .026 ± .013			135 ± 65 (new measurements in progress)
Beijing	7.7 ± .6 6.8 ± .6	.016 ± .010		134 ± 80	340 ± 192
St. Petersburg		.009 ± .005			(measurement in progress)
ANL/Greenwood					
Jülich					
Lanzhon University	6.04 ± 32				
Harwell/Patrick	5.9 ± .6	?			

+ all cross-sections reported to the CRP were renormalized to the new half-life of 433 years for ^{108m}Ag

Table 2

Cross Sections below 14 MeV
(Status of the data as available at the 2nd CRP meeting)

$^{63}Cu(n,p)^{63}Ni$	Jülich/Debrecen measurements in progress
$^{94}Mo(n,p)^{94}Nb$	
$^{109}Ag(n,2n)^{108m}Ag$	38.5 mb ± 10.6% at 10.3 MeV ANL/LANL
$^{151}Eu(n,2n)^{150m}Eu$	215 ± 17 mb at 10.3 MeV ANL/LANL; 9.7 - 10.7 MeV Jülich/Debrecen
$^{153}Eu(n,2n)^{152g}Eu$	
$^{159}Tb(n,n2)^{158}Tb$	575 ± 57 mb at 10.3 MeV ANL/LANL; 8.7 - 10.7 MeV Jülich/Debrecen
$^{179}Hf(n,2n)^{178m2}Hf$	
$^{182}W(n,n'\alpha)^{178m2}Hf$	
$^{158}Dy(n,p)^{158}Tb$	
$^{193}Ir(n,2n)^{192m2}Ir$	
$^{187}Re(n,2n)^{186m}Re$	

Table 3

(n,γ) Reactions
(Status of the data as available at the 2nd CRP meeting)

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

E_n = 29 - 1100 keV	Chengdu) reasonable agreement in
E_n = 700 - 2000 keV	St. Petersburg) overlapping region
$^{165}Ho(n,\gamma)^{166m}Ho$	2.92 ± 0.6 mb at E_n = 674 keV
$^{191}Ir(n,\gamma)^{192m2}Ir$	no work done

(b) For the $^{182}W(n,n'\alpha)^{178m2}Hf$ reaction now 5 cross section values are available. The mean of those values will satisfy the need.

(c) For the $^{187}Re(n,2n)^{186m2}Re$ reaction one measurement has been reported and two others are in progress (in Russia and in the P.R. of China).

(d) Due to impurity problems the $^{158}Dy(n,p)^{158g}Tb$ reaction is with present experimental techniques not measurable. The contribution of this process in comparison to the $^{159}Tb(n,2n)^{158}Tb$ process is negligible. This reaction is, therefore, discarded.

(e) For capture reactions no new data have been reported; the status is thus the same as given in the previous report.

(f) Measurements on $^{63}Cu(n,p)^{63}Ni$ are on-going. In view of the large difficulties in activation measurements, direct measurements of emitted protons at $E_n < 8$ MeV should be considered as an alternative.

(2) Decay Data

The half-life of ^{108m}Ag has been slightly revised by PTB. It is given now as 433 $\pm$ 15 years. The half-life value of ^{150m}Eu has been reported from Los Alamos as 36.9 $\pm$ 0.9 years, slightly larger than the presently accepted value. It is further stressed that uncertainties in half-lives and branching ratios are still among the largest sources of uncertainty for some cross sections included in the CRP.

(3) Plans for future work

(a) IRK will update and extend the evaluation of 14 MeV cross sections in the near future.

(b) Vonach/Mannhart, Qaim/Csikai will consider to perform (n,2n) cross section measurements on $^{109}Ag(n,2n)^{108m}Ag$, $^{151}Eu(n,2n)^{150m}Eu$ and $^{159}Tb(n,2n)^{158}Tb$ in the 10 to 12 MeV region, if possible using highly enriched isotopes as target materials.

(c) On-going measurements at St. Petersburg, JAERI, Jülich, Debrecen and Beijing at 14 MeV and other energies will be continued and the results presented at the next CRP meeting.

(d) $^{151}Eu(n,\gamma)^{152}Eu$ and $^{177}Hf(n,\gamma)^{178m2}Hf$ at 179 keV and higher energies will be completed at Sichuan University (Chengdu) and IAE (Beijing) PR China.

(e) Measurement of $^{63}Cu(n,p)$ reaction by direct proton detection at $E_n < 8$ MeV will be considered at IRMM Geel.

(f) The question of background neutrons and consideration of neutron energy scale are still being addressed at ANL. In this context further cooperative work

between Jülich and Debrecen will also be done on d-d neutrons in the energy range of 10 to 12 MeV.

(g) Studies on $^{28}Si(n,n'p)^{27}Al$ process will be considered at Los Alamos. Results on the $^{27}Al(n,n'\alpha)^{23}Na$ reaction will be reported by Vonach.

B. WORKING GROUP ON CROSS SECTION CALCULATIONS

Chairman: M.B. Chadwick (Lawrence Livermore National Laboratory)

Members: F.M. Mann (Westinghouse Hanford Company, Richland)
A.B. Ignatyuk (Obninsk)
G. Reffo (E.N.E.A. Bologna)
M.A. Gardner (Lawrence Livermore National Laboratory)
A.B. Pashchenko (IAEA, Vienna)

(1) Status of the cross section calculations

(a) In accordance with recommendation (4h) from the previous CRP meeting in Vienna (see INDC(NDS)-263/G, p. 14), M.B. Chadwick has calculated excitation functions of reactions measured by D.L. Smith and the ANL/LANL/JAERI collaboration. Charged particle producing reactions were also considered, as was the theoretical implication of using the Feshbach-Kerman-Koonin theory in evaluation work. See contributed paper for full details.

(b) In accordance with recommendation (4j) from the previous CRP meeting, the Obninsk group calculated transmutation cross sections for a number of long-lived radionuclides. The isomeric ratios for different reactions to a given isomeric state were investigated, along with their energy dependences. Systematics of isomeric ratios for threshold reactions were investigated. See contributed paper for full details.

(c) As Dr. Maino was not present at the meeting, progress on calculating the reactions described in (4g) of the previous CRP recommendations is not known. We recommend that Dr. G. Reffo should calculate the reactions $^{109}Ag(n,2n)^{108m}Ag$, $^{63}Cu(n,p)^{63}Ni$, $^{62}Ni(n,\gamma)^{63}Ni$.

(2) Plans for future work

(a) By the end of May 1993, M.B. Chadwick and A.V. Ignatyuk will consider all theoretical calculations of excitation functions for the reactions considered by the CRP, and will provide preliminary recommendations for theoretical excitation functions. In addition to the (n,2n) and (n,p) reactions considered by the CRP, the $^{178}Hf(n,n')^{178m}Hf$ will be calculated as this contributes to the measured ^{178m}Hf cross section for neutron energies below 14 MeV.

(b) Differences between all theoretical calculations will be investigated in detail before the next CRP. All input parameters for the theoretical calculations will be sent to M.B. Chadwick before the end of summer 1993, and will be compiled into a computer file which will allow the reproduction of all theoretical results.

(c) Differences between experimental and theoretical results for excitation functions will be investigated before the next CRP meeting. At present the theoretical calculations exceed measured cross sections in the 10-12 MeV range.

(d) The IAEA NDS will organize an informal meeting for all CRP participants during the May 1994 Nuclear Data Conference at Gatlinburg. Our progress in theoretical calculations will be discussed.

(e) The reactions $^{27}Al(n,n'\alpha)$, $^{45}Ca(n,\alpha)$ will be calculated due to their great importance in proposed fusion reactors.

C. WORKING GROUP ON CHARGED PARTICLE REACTIONS

Chairman: P. Obložinský (Bratislava, presently IAEA/Nuclear Data Section)

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The RCM recognizes important contributions to the understanding of the role of charged particle reactions on production of radioactive inventories in fusion reactor materials (contributions presented by P. Obložinský and B. Guzhovskij). IAEA should encourage KfK Karlsruhe to continue its work (in collaboration with Bratislava) on sequential (x,n) reactions.

The RCM recommends to extend the current CRP by considering charged particle reactions. The following 4 tasks have been identified:

(1) Impact of sequential charged particle reactions on production of radioactivities should be demonstrated in realistic materials (Li with impurities, Be with impurities, V5Cr5Ti and SS316).

(2) Current KfK libraries should be compared with experimental data for light elements (from hydrogen to oxygen).

(3) FISPACT code should be extended so that sequential charged particle reactions can be included and made transparent to the user. In addition the decay library needs to be extended to include nuclides only formed by sequential charged particle reactions (currently 213 isotopes). It will also be necessary in the future to extend EAF to

include cross section data for long lived targets that are only formed by sequential charged particle reaction.

(4) Estimates should be performed of induced activities on the first wall due to direct charged particles (p and α) irradiation. Materials to be considered are Be, graphite, V5Cr5Ti and SS316.