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

Summary Report of the Third IAEA Research Coordination Meeting
organized by the International Atomic Energy Agency
in co-operation with the V.G. Khlopin Radium Institute,
St. Petersburg, Russia and held in St. Petersburg
from 19 - 23 June 1995

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

November 1995

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ABSTRACT

The present report contains the Summary of the Third and Final 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 the V.G. Khlopin Radium Institute and held in St. Petersburg, Russia, from 19-23 June 1995. This RCM was organized by the IAEA Nuclear Data Section (NDS), with the cooperation and assistance of local orgainzers from V.G. Khlopin Radium Institute.

The papers prepared and presented by the participants at the meeting will be published as separate report.

November 1995

Contents

Third IAEA Research Co-ordination Meeting on "Activation Cross Sections for the Generation of Long-lived Radionuclides of Importance in Fusion Reactor Technology" held at the V.G. Khlopin Radium Institute, St. Petersburg, 19-23 June 1995.

1. Introduction

Activation of reactor materials due to the neutron field generated by the 14 MeV deuterium-tritium neutrons is a major issue concerning the development of fusion as a long-term energy source. It will influence 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 requirement the IAEA formed a Co-ordinated Research Program (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 and succeeded in obtaining the participants of 18 laboratories from nine member countries in this very specific task. The reactions are as following:

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

The first Research Co-ordination Meeting (RCM) was held in Vienna in November 1991. In April 1993, the second RCM took place in Del Mar, California. This report documents the summary of the third and final RCM of this program.

2. Objectives of the Meeting

The purpose of this meeting was to report, discuss and evaluate the results of the research carried out by each participating laboratory under this CRP, to review the status of cross sections for the 16 activation reactions, of special importance to fusion reactor technology, leading to long-lived radionuclides and to prepare the final report summarizing the results of the CRP to the IAEA. The meeting agenda is given below as Attachment 1.

3. Organization of the Meeting

The final Research Co-ordination Meeting of the CRP was organized by the IAEA Nuclear Data Section with the co-operation and assistance of local organizers from the V.G. Khlopin Radium Institute, KRI, and held in St. Petersburg from 19-23 June 1995.

The meeting was attended by ten chief scientific investigators involved or their representatives (Dr. G. Reffo attended the meeting for Dr. G. Maino) and by five observers and/or consultants. The CRP members were: H. Vonach (Austria), Lu Hanlin (China), S. Qaim (Germany), J. Csikai (Hungary), G. Reffo (Italy), Y. Ikeda (Japan), A. Ignatyuk (Russia), A. Rimski-Korsakov (Russia), R. Forrest (U.K.), D. Smith (U.S.A.). M. Blann (U.S.A.) contributed as a consultant and J. Kopecky (Netherlands), N. Kornilov, K. Zolotarev and A. Filatenkov (all from Russia) and E. Cheng (U.S.A.) participated as observers. The complete list of participants and their affiliations are given in Attachment 2.

4. Meeting Proceedings and Results

The meeting was opened by Dr. A.A. Rimski-Korsakov, the Deputy Director of the V.G. Khlopin Radium Institute, St. Petersburg. After the welcome by A.B. Pashchenko on behalf of the Agency, Dr. S. Qaim, acting Director of the Institute of Nuclear Chemistry at the Forschungszentrum Jülich, Germany, was selected to be the Chairman of the meeting.

At the two previous CRP meetings most of the discussion was centered on preliminary values. The most important task of each participant during the St. Petersburg RCM was to provide final values of all the results from measurements and model calculations and prepare the contribution to the Final Report summarizing the results of the CRP to the IAEA.

The first day and first part of the second day of the meeting were devoted to presentations of progress reports by CRP members on Measurements (Session 1) and on Theoretical Calculations and Evaluations (Session 2). The problems of activation concerns and cross section data needs for fusion reactor technology were discussed on Tuesday morning (Session 3) in the paper given by E.T. Cheng. The presentation of R.A. Forrest was devoted to the development of the European Activation System (EASY) for calculations of the production of radioactive inventories for fusion devices. His paper considered the effect of sequential charged particle reactions on realistic materials. Technical conclusions and recommendations for specific CRP reactions and the full text of the meeting conclusions and recommendations are given below.

It was agreed that the proceedings of the meeting should be published as an IAEA NDS report within several months after the final CRP Meeting. The texts of the presentations and final results will be reproduced directly from the authors' manuscripts. E. Cheng suggested that in addition to the IAEA report, the papers on the subject of long-lived activation cross-sections be also submitted to Journal on Fusion Engineering and Design for consideration as a special issue. This would give a wider distribution of the papers to the fusion researchers.

The major item of the next days was preparation of the Final Report summarizing the results of the CRP (Session 4). For this purpose, on Tuesday afternoon, the Chairman, S. Qaim, organized two Working Groups for discussion and drafting of three different chapters of the final report:

- Executive Summary
- Summary of the experiments performed under the auspices of the CRP
- Summary on Theory and Systematics.

The draft of the Final Report was discussed and adopted on Friday at the joint Session of the meeting.

It was emphasized that the original goals of the CRP were completed. The program was very successful at a relatively low cost to the IAEA as it has involved only research agreements. It was concluded, in particular, that

- by limiting 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 establishment of the CRP has helped initiation of several new interlaboratory collaborations and strengthened existing relationships. In this era of diminished funding, facilities and manpower, this very important consequence of the CRP will have benefits which extend far beyond the specific limits of the CRP;

- this CRP has not only produced very useful results for most of the 16 reactions selected but led to the generation of new data for many additional reactions. Furthermore, it has stimulated the development of new measurement and data analysis techniques which have broad applicability for future nuclear data endeavors.

It was agreed to publish the Final Report separately as INDC(NDS)-344 and produce another shortened version which could be sent to a journal, e.g. Nuclear Science and Engineering for journal publication, with all CRP members as authors.

5. Future Activity

In the meantime, extended data needs for cross sections for the generation of long lived nuclides have been presented by the fusion community. Dr. E. Cheng in his lecture "Activation Concerns and Cross Section Data Needs for Fusion Reactor Technology" delivered at the meeting presented a list of neutron activation reactions for which new cross section measurements and evaluations are needed to meet requirements relevant to safety, maintenance and waste disposal. The participants were informed by A.B. Pashchenko that the INDC meeting, held in Vienna in April 1995, has endorsed with high priority the proposal of the Nuclear Data Section to use the well-established structure of this CRP and address these

new tasks by initiation in 1997 a new CRP on Activation Cross Sections for Fusion Technology.

More emphasis now needs to be placed on the short-lived products for consideration of reactor afterheat and transport of dose (Report INDC(USA)-106/L).

6. Award

Dr. Syed M. Qaim received the honorary fellowship ("Civis Universitatis honoris causa") of the Kossuth University in Debrecen, Hungary, in recognition of many years of fruitful scientific collaboration. Among many other results, as Prof. Csikai emphasized in his speach at the awarding ceremony, the precise cross-section measurements of many important nuclear reactions which were included in the international nuclear data files. Participants warmly applauded this event.

7. Acknowledgements

The CRP members wish to thank the Agency for focusing much needed attention on activation concerns and nuclear data needs for technology. The final RCM had full and efficient support of the local organizers. The participants expressed their gratitude and appreciation to the staff of the V.G. Khlopin Radium Institute, expecially to Drs. A.A. Rimski-Korsakov, A.A. Filatenkov and S.V. Chuvaev for their interest, special arrangements and personal contributions to the meeting.

Third IAEA Research Co-ordination Meeting on "Activation Cross Sections for the Generation of Long-lived Radionuclides of Importance in Fusion Reactor Technology" held at the V.G. Khlopin Radium Institute, St. Petersburg, 19-23 June 1995.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

General Conclusions

G.1. By limiting 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.

G.2. The establishment of the CRP has spawned several new interlaboratory collaborations and strengthened existing relationships. In this era of diminished funding, facilities and manpower, this very important consequence of the CRP will have benefits which extend far beyond the specific limits of the CRP.

G.3. The need for enriched (isotopic) samples has been demonstrated in efforts to provide data for several of the reactions considered. This makes sense from a technological point of view. Unfortunately, pricing policies for the loan or sale of these materials from those countries with the largest stockpiles (U.S.A. and Russia) makes it prohibitively expensive to use enriched materials. This is a very important issue which must be addressed, otherwise future impact in the area of nuclear data measurements will be limiting and negative. It is recommended that the IAEA investigate possible means for alleviating this problem. Qaim will write to ECN.

G.4. This CRP has not only produced very useful results for most of the 16 reactions selected but led to the generation of new data for many additional reactions. Furthermore, it has stimulated the development of new measurement and data analysis techniques which have broad applicability for future nuclear data endeavors.

Technical Conclusions

T.1. The approach of determining cross section values near 14 MeV from the evaluation of experimental data or obtaining estimates from systematics and/or the manipulation of partial cross sections (i.e. ground state and isomeric-state formation) has been demonstrated to be very successful in the case of threshold reactions.

T.2. Given a reasonable determination for the 14 MeV region, it has been demonstrated that evaluated excitation functions, based on nuclear-model calculations provide quite reasonable representations of the cross sections from threshold upward for (n,2n)

reactions when these curves are normalized at 14 MeV. This has been confirmed within the CRP for several of the reactions via comparisons with new data in the 9-12 MeV range. However, the situation for other threshold reactions with smaller cross sections, e.g. (n,p), (n,α) or (n,n'α) is less clear. The shapes of these excitation curves below 14 MeV are influenced to a much greater extent by reaction channel competition.

T.3. Although data for several (n,γ) activation reactions have been provided under the auspices of the CRP, it is clear that this information is inadequate to define the excitation functions because of the complex nature of these curves for non-threshold type reactions of this nature. The data provided are in the keV-to-MeV energy range, i.e. above the resonance region in all cases. However, in a fusion reactor, the production of radioactivities by (n,γ) reactions will surely be influenced by the thermal and epithermal capture cross section (1/v region) and by the detailed nature of the capture resonance structure. Generally speaking it should be possible to fix the normalization of the cross section below the resonance region by careful measurements at thermal energy in a reactor. For this work one can use quite small samples, taking advantage of the high flux environments of available research reactors. The resonance region is quite another matter. In selected cases where total capture is the process of interest, and chemically pure enriched samples of adequate size can be obtained, it would be possible to make very detailed measurements of the cross sections in the resonance region.

Recommendations

A. General Recommendations

R.1. It is recommended that the fusion community utilize the computer codes available for the calculation of activation product yields in representative fusion reactor spectra to compare the integral predictions for the various suggested differential evaluations to be considered for the selection of the FENDL library. In particular, the response for different neutron energy ranges is very important. This is especially true for capture activation owing to the greatly different character of the thermal/epithermal, resonance and fast-neutron regions.

B. Recommendations for Specific CRP Reactions

B.1. **^{27}Al(n,2n)**
Use data near 14 MeV and Obninsk evaluation for higher energies. Vonach will do evaluation. Available September 1995.

B.2. **^{63}Cu(n,p)**
Use recommendation in Theory Section till such time as experimental data from Jülich available. Expected completion February 1996.

B.3. **^{94}Mo(n,p)**
Vonach to check renormalization - essentially available now.

B.4. **^{109}Ag(n,2n)**
Vonach to check renormalization - adopted as is.

B.5. **^{179}Hf(n,2n)**
Vonach to check renormalization - adopted as is.

B.6. **^{151}Eu(n,2n)**
Final experimental data to be sent to Vonach by 1 September. Final evaluation available February 1996.

B.7. **^{153}Eu(n,2n)**
Vonach to check renormalization - adopted as is.

B.8. **^{159}Tb(n,2n)**
Vonach to check renormalization - adopted as is.

B.9. **^{182}W(n,n'α)**
Use recommendation in Theory Section. Available in February 1996.

B.10. **^{158}Dy(n,p)**
Use available theoretical curve. Available now.

B.11. **^{193}Ir(n,2n)**
Vonach to check renormalization - adopted as is.

B.12. **^{187}Re(n,2n)**
Vonach to check renormalization - adopted as is.

B.13. **^{62}Ni(n,γ)**
ENDF/B-VI

B.14. **^{98}Mo(n,γ)**
ENDF/B-VI

B.15. **^{165}Ho(n,γ)**
Ignatyuk and Chadwick to finalize, available February 1996.

B.16. **^{191}Ir(n,γ)**
Ignatyuk and Chadwick to finalize, available February 1996.

The final recommended cross sections resulting from above actions will be given in the Final Report of the CRP which will be published as INDC(NDS)-344 in the first half of 1996.

Attachment 1

Third and Final IAEA Research Co-ordination Meeting on

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

St. Petersburg, Russia, 19-23 June 1995
Organized in co-operation with the V.G. Khlopin Radium Institute
St. Petersburg, Russia

AGENDA

Monday, 19 June

11:30 - 12:00 **Opening Session**

Opening remarks by Alexander A. Rimski-Korsakov, Deputy Director of the V.G. Khlopin Radium Institute and Anatoly B. Pashchenko, IAEA Nuclear Data Section

- Election of Chairman
- Adoption of Agenda and Time Schedule
- Announcement of Organizational Matters

12:00 - 13:00 **Session 1** - Progress Reports by CRP Participants on Measurements (15 minutes each speaker)

(1) D.L. Smith, Argonne, U.S.A.:
"Neutron Activation Cross Sections for Copper, Europium, Hafnium, Iron, Nickel, Silver, Terbium and Titatnium from the Argonne, Los Alamos and JAERI Collaboration"

(2) Y. Ikeda, JAERI, Japan:
"The Summary of Activation Cross Section Measurements at FNS"

(3) J. Csikai, Debrecen, Hungary:
"Measured, Estimated and Calculated Cross Sections for the Generation of Long-lived Radionuclides in Fast Neutron Induced Reactions"

(4) Lu Hanlin, Beijing, China:
"Activation Cross Sections for Generation of Long-lived Radionuclides"

13:00 - 14:30 **Lunch**

14:30 - 15:30 **Session 1** (cont'd)

(5) Dr. S.M. Qaim, Jülich, Germany:
"Progress Report on Measurement of Cross Sections for the Formation of some Long-lived Activation Products in Fast Neutron Induced Reactions"

(6) A.A. Filatenkov, Khlopin Radium Institute:
"Measurements of some Activation Cross Sections for some Reactions of Importance for Fusion Reactor Technology"

Discussion

15:30 - 16:00 **Coffee Break**

16:00 - 18:00 **Session 2** - Progress Reports on Theoretical Calculations and Evaluations

(1) A.V. Ignatyuk, Obninsk, Russia:
"Analysis of Evaluations for Al-27(n,2n), Cu-63(n,p), Dy-158(n,p), W-182(n,n'alpha) and Ho-165(n,gamma)Ho-166m, Ir-191(n,gamma)Ir-192m2 Reactions"

(2) M. Blann, Livermore, U.S.A.:
"Calculated Excitation Functions of Neutron Induced Reactions on Cu-63, Mo-94, Dy-158 and Tb-159 from 1-20 MeV Incident Energy"

(3) G. Reffo, Bologna, Italy:
"Isomeric Ratio for the Reaction Ag-107(n,2n)"

Discussion

Tuesday, 20 June

09:00 - 10:00 **Session 3** - Activation Concerns and Cross Section Data Needs for Fusion Reactor Technology

(1) E.T. Cheng, TSI Research, U.S.A.:
"Activation Concerns and Cross Section Data Needs for Fusion Reactor Technology"

(2) R.A. Forrest, Culham, UK:
"Development of EASY to Include Sequential Charged Particle Reactions and Examples of its Use with Realistic Materials"

Discussion

10:00-13:00 **Session 4** - Preparation of Final Report Summarizing the Results of the CRP

- General discussion (contents, chapters, sections)
- Formation of Working Groups to draft the Summary Report

13:00 - 14:30 **Lunch**

14:30 - 18:00 **Session 4** (cont'd)

- Working Group's discussions and drafting of different chapters of the final report

Wednesday, 21 June

09:00 - 18:00 **Session 4** (cont'd)

- Working Group's Sessions on drafting of final report

Thursday, 22 June

09:00 - 13:00 **Session 4** (cont'd)

- Completion of Final Report
- General discussion and corrections

13:00 - 14:30 **Lunch**

14:30 **Visits to the laboratories and facilities of the Khlopin Radium Institute**

Friday, 23 June

09:00 - 16:00 **Session 5** - Final Consideration, Correction and Adoption of Final Report

- Discussion on Future Activity
- Closing of RCM

Attchment 2

Third IAEA Research Co-ordination Meeting on
"Activation Cross Sections for the Generation of Long-lived Radionuclides of Importance in Fusion Reactor Technology"

St. Petersburg, Russia
19 to 23 June 1995

Scientific Secretary: Anatoly B. PASHCHENKO

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