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IMPROVEMENT OF MEASUREMENTS, THEORETICAL COMPUTATIONS AND EVALUATIONS OF NEUTRON INDUCED HELIUM PRODUCTION CROSS SECTIONS

Summary Report of the Second Research Co-ordination Meeting organized by the International Atomic Energy Agency in co-operation with the China Institute of Atomic Energy and held in Beijing, China, from 1 to 4 November 1994

Prepared by
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February 1995

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ABSTRACT

The report contains the Summary of the 2nd Research Co-ordination Meeting (RCM) of the IAEA Co-ordinated Research Programme (CRP) on "Improvement of Measurements, Theoretical Computations and Evaluations of Neutron Induced Helium Production Cross Sections". The meeting was organized by the IAEA Nuclear Data Section (NDS) with co-operation and assistance of local organizers from the China Institute of Atomic Energy and held in Beijing, China, from 1 to 4 November 1994.

The purpose of the RCM was to discuss the results obtained by the participating institutes under the CRP, to review the status of helium production cross section data and to work out a coordinated working programme for the participants. The meeting agenda, conclusions and recommendations, and the list of participants are presented in the summary report.

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February 1995

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2nd Research Co-ordination Meeting of the Agency's CRP on "Improvement of Measurement, Theoretical Computations and Evaluations of Neutron Induced Helium Production Cross Sections"

Beijing, 1-4 November 1994

(1) Organization of the Meeting

The 2nd Research Co-ordination Meeting (RCM) of the Co-ordinated Research Programme on "Improvement of Measurements, Theoretical Computations and Evaluations of Neutron Induced Helium Production Cross Sections" was organized by the IAEA Nuclear Data Section with co-operation and assistance of local organizers from the China Institute of Atomic Energy and held in Beijing, China, from 1 to 4 November 1994.

(2) Objectives of the Meeting

The purpose of the RCM was to discuss the results obtained by the participating institutes since the first RCM (Debrecen, November 1992), to review the status of helium production cross section data and to work out a co-ordinated working programme for the participants.

(3) Meeting Proceedings and Results

The meeting was attended by nine CRP members involved and by four observers. The complete list of participants and their affiliations are given in Attachment 3. The meeting was opened by Professor Xu Jincheng, Director of Nuclear Physics Department. After the welcome by A.B. Pashchenko on behalf of the IAEA, Professor H.K. Vonach was elected to be Chairman of the meeting.

The agenda of the RCM included scientific and technical presentations of participants, discussions on the status of helium production cross sections and discussions on future tasks and co-ordinated actions of participants. The agenda is given as Attachment 2.

After the reports from participants were presented and discussed, the actions from the previous meeting (see report INDC(NDS)-273/G, March 1993) were reviewed. Finally it was concluded that a considerable part of the experimental and theoretical work proposed in the recommendations of the first CRP meeting (Debrecen, November 1992) has been successfully completed.

The discussions were guided by the following order:

- opening session
- review of (n,xα) measurements and theoretical interpretations
- review of the theoretical models and evaluations
- general discussion on the future scope of the CRP
- conclusions and recommendations
- final considerations

The above topics were discussed during the meeting.

The following main comments are drawn from notes and discussions:

- The progress as summarized at the meeting appears to represent a significant achievement in the understanding of the computational problems faced by evaluators of (n,α) cross sections.

- New results for double-differential α-emission cross sections of ^{56}Fe for neutron energies from threshold to 30 MeV were reported by Haight, Los Alamos, and corresponding results for natural Fe for neutron energies up to 14 MeV were presented by Baba (Tohoku University). In addition, a helium accumulation measurement at En = 10 MeV was also reported by Haight. These results are in good agreement with each other and previous α-production measurements. Thus there exists now an adequate experimental database for the neutron-induced α-production in iron.

  This was demonstrated by Vonach who presented a quantitative evaluation of the ^{56}Fe(n,α) cross section showing that this is known to about 5% in the energy range between threshold and 14 MeV.

- New measurements of the double differential α-emission cross section were reported by Baba (Tohoku University) for nat-Ni between threshold and 14 MeV, and Goverdovskij (IPPE, Obninsk) for ^{58}Ni for neutron energy up to 7 MeV. In addition new results for nat-Ni were obtained outside the CRP by Tang (China, Peking University) at 5 MeV and by Wattecamps at IRMM, Geel. Furthermore the double differential cross sections of both ^{58}Ni and ^{60}Ni have recently been measured by Haight from threshold to more than 30 MeV, which, however, still have to be analyzed.

  It can be expected that (after analysis of the Los Alamos results) the experimental data for α-emission from Ni and its main isotopes ^{58}Ni and ^{60}Ni will be adequate for all applications.

- Double-differential α-emission cross sections for ^{50}Cr between threshold and 14 MeV were reported by Baba. No measurements for ^{52}Cr, the main isotope of Cr, have been performed so far due to the lack of suitable targets. Such targets, however, have recently been obtained by Vonach, who will make them available to all interested CRP members.

- New measurements of double-differential α-emission cross sections for carbon and oxygen up to 30 MeV have been performed by Haight at WNR, Los Alamos. The (n,α2,3) cross sections at E = 14 MeV have been determined accurately by (n,n'γ) measurements by Hlavac (Bratislava) and measurements of the excitation functions for this reaction were performed at Los Alamos also by (n,n'γ) reactions. In addition, outside of the CRP measurements of proton and deuteron production by 40-70 MeV neutrons have been reported by Meulders from the University of Louvain, Belgium.

- Activation cross sections for (n,α) reaction were measured for 30 nuclei at 14.7 MeV incident energy by Csikai (Debrecen University). He measured in a co-operation between Debrecen and Jülich excitation functions for ^{63}Cu(n,α)^{60m}Co and ^{65}Cu(n,α)^{62m,g}Co reactions over the energy range of 6-15 MeV. For the ^{63}Cu(n,α)^{60m}Co reaction all the data between 6-12 MeV were measured for the first time except for a single value at 8.2 MeV. The excitation functions of ^{90}Zr(n,α)^{87m}Sr and ^{94}Zr(n,α)^{91}Sr reactions were checked on a few points between 6.8 - 14.5 MeV.

- In addition high purity C, Al, $KHNO_3$, Zn, Ni, Cu, Mo, Si_3N_4 and SiO_2 samples were irradiated in Debrecen with 14.6 MeV neutrons to produce long-lived radionuclides by (n,α) reactions. The measurements of the samples activities, including the radiochemical separation, are in progress.

- Activation cross sections for 10 dosimetry reactions including three (n,α) reactions have been measured by Chiba in the energy range 9-12 MeV using the H(B^{11},n)^{11}C reaction as neutron source.

More detail on this work is given in about 18 contributions to this meeting.

After the work done by participants under the CRP was reviewed, the future scope of the CRP was discussed. The participants concluded that this CRP is being very successful due to the programming contributions of its members to the research of helium production. The meeting expressed the opinion that the original goals of the CRP are still valid and due to the well-established structure of this programme have to be fulfilled as completely as possible.

In addition, the participants agreed that the data needs for medical purposes extend to considerably higher energies ($\approx$ 250 MeV) than assumed previously and thus propose ^{12}C(n,xα) and ^{16}O(n,xα) studies up to this energy.

On Thursday morning, the Chairman, H.K. Vonach, organized two working groups to discuss the following two days in parallel sessions assigned issues and to prepare the draft conclusions and recommendations and a plan of actions for final consideration. The working groups with their chairmen were decided as follows:

- Experimental measurements of (n,α) cross section energy and angular distributions
  (Chairman: H.K. Vonach)

- Theoretical computations and evaluations
  (Chairman: C.Y. Fu)

The full text of the meeting's conclusions and recommendations was prepared as working groups' reports and is given as Attachment 1. A detailed plan of the coordinated work in order to achieve the objectives of the CRP in the best possible way and the related actions assigned to the CRP members are listed in the final reports.

(4) Acknowledgements

The RCM had full and efficient support of the local organizers. The participants expressed their gratitude and appreciation to the staff of the Chinese Nuclear Data Center, especially to Dr. Zhao Zhixiang, Ms. Wei Ling and Drs. Yu Baosheng and Liu Tong for their interest, special arrangements and personal contributions to the meeting.

Attachment 1

CONCLUSIONS AND RECOMMENDATIONS

2nd Research Co-ordination Meeting of the Agency's CRP on "Improvement of Measurement, Theoretical Computations and Evaluations of Neutron Induced Helium Production Cross Sections"

Chairman: H.K. Vonach

I. Report of Working Group on Theoretical Computations and Evaluations

Chairman: C. Y. Fu

Working Group Members

A.B. Pashchenko
R. Capote Noy
T. Liu
H. Vonach
B.S. Yu
A.V. Zelenetskij
Z. Zhao

(1) Progress Summary

The working group on computation and evaluation concluded two years ago at Debrecen, Hungary, that the most serious problem in accurately predicting the (n,α) cross sections was in the nuclear level densities used for the calculations. Small changes in the level densities used for competing channels, particularly (n,n'), can result in substantially larger changes in the calculated (n,α) cross sections. For this reason, a large part of the planned research program is related to nuclear level densities.

The Gilbert-Cameron (GC) and Back-Shifted Fermi Gas (BSFG) formulas for nuclear level densities, equally popular among cross section evaluators, differ in excitation energy dependence (shape). By forcing agreement of these two level densities at two selected energies, the shape effects on calculated (n,α) cross sections and α-emission spectra can be examined. Fu has shown for ^{58}Ni using the TNG code that this shape difference in level-density formulas can change both the calculated (n,α) cross sections and α-emission spectra by up to 60% below incident neutron energies of 20 MeV. It is concluded that, in addition to the well known problems in level density parameters, the level density formulas themselves are also problematic in nuclear model calculations.

Capote performed combinatorial calculations (CC) for ^{58}Co, ^{58}Fe, and ^{58}Ni using quasi-particle levels. The results were compared with the Generalized Superfluid Model (GSM) for nuclear level densities and the BSFG model. Except for ^{58}Co, the absolute magnitudes of all results are in good agreement with the calculations, using empirical formulations. The CC shape tends to favor the GSM. Capote also calculated the ^{58}Ni(n,n'), (n,p), and (n,α) cross sections. His (n,α) cross section is in agreement with EFF-2 is shape and Zelenetskij's calculation.

Zelenetskij is dealing with the (n,α) cross section calculations for the ADL activation data library that contains over 15,000 reactions, mostly generated by model calculations. For the (n,α) reactions, many computational problems exist. Three commonly used sets of global optical model parameters yield substantially large differences in calculated neutron absorption cross sections. Small differences in the Coulomb barrier parameters can result in rather large differences in fission spectrum averages of calculated (n,α) cross sections. For heavy nuclides, the direct reaction mechanism is very important for (n,α) cross section calculations but is poorly understood.

Vonach has evaluated the ^{56}Fe(n,α) cross section using the Bayes theorem employed in the GLUCS code. The EFF-2 evaluation was used as the prior. Experimental data available up to 1992 was combined with the prior at that time. The resulting evaluation was further updated in 1994 with newer data as a second step. It was demonstrated that in each step, the uncertainties in the evaluated results are reduced. The uncertainties in the new evaluation are less than 5%.

Zhao has developed a semi-empirical formula for (n,αx) cross sections for the mass range between 23 and 200. Two parameters (functions of Z and A) are used. Uncertainties in the resulting cross sections are based on the derivations of local parameters from the global parameters. Correlations between the two parameters are based on the moments method. However, the formula cannot be used for odd-odd targets because too few data exist.

Liu presented his auxiliary plotting code of the UNF code - UNFTOOLS. The code can plot curves of cross section, spectrum, and double differential cross section directly from the UNF output files. The code can also plot experimental data and data in ENDF/B format (only for MF = 3 and 4) simultaneously.

Yu presented the CENDL-2 evaluations for a large body of (n,α) cross sections.

(2) Further Coordinated Research

Fu will continue investigating the level-density shape effects on calculated cross sections by adding the GSM as a third level density option to the TNG code and perform similar comparisons as described in Section 1. It is hoped that this effort can shed some light on shape differences between the GC and BSFG formulas of nuclear level densities.

Capote will further investigate his combinatorial level density calculations such that s-wave level spacings near the neutron binding energy for ^{52}Cr, ^{56}Fe, ^{58}Ni, and ^{60}Ni can be better predicted. The results of these predictions could be used to check the level density systematics that is the only method being used for these nuclides.

In view of Capote's expertise on combinatorial level density calculations, Pashchenko suggests that Capote be invited as a member of the level density subgroup (subgroup 16) of the OECD NEANSC International Evaluation Working Party. Fu is the coordinator of that subgroup. In the meantime, Capote is applying for an IAEA fellowship to work with G. Reffo in Bologna, Italy, on combinatorial level density calculations. This work would benefit Capote's involvement in this CRP as well as benefit the new IAEA CRP on input parameter data for nuclear model calculations.

Zelenetskij will attempt to develop a semi-empirical formula to parameterize the direct reaction contributions to the (n,α) cross sections. For this purpose, the working group asks the members of the experimental group, in particular Baba and Haight, send their new data for Y, Nb and other targets to Zelenetskij as soon as available.

Now that the experimental data of Baba, Haight, and Goverdovskij near the reaction threshold for ^{58}Ni are available, it will be very useful to provide a theoretical interpretation of the cross section behaviour below the Coulomb barrier. Capote and Zelenetskij will work together in this direction.

Zhao will improve his semi-empirical (n,α) model with more recent experimental data and investigate possible deformation effects. At the suggestion of Vonach, Zhao will re-examine the uncertainty analysis that would include more statistical fluctuations in the calculated cross sections.

In some cases the (n,α) cross sections are important for the production of long-lived radionuclides. Yu plans to evaluate the ^{62}Ni(n,α)^{59}Fe and ^{63}Cu(n,α)^{60}Co cross sections based on newly measured data.

Pashchenko asks Fu, as coordinator of the subgroup on level densities of the NEANSC International Evaluation Working Party, that he correlate the efforts of the NEANSC subgroup and the working group on theoretical computations and evaluations of this CRP.

Fu suggests that Vonach consider an evaluation of ^{58}Ni(n,α) as he has done for ^{56}Fe(n,α) since both cases have newly available experimental data that are ideal for Bayes theorem analysis. A ^{58}Ni(n,α) evaluation accurate to 5% would impose a constraint to the level-density investigations for this nuclide described above. Vonach has agreed to do so.

(3) Conclusion

The progress summarized in Section 1 appears to represent a significant achievement in understanding the computational problems faced by evaluators of (n,α) cross sections. The proposed further research described in Section 2 fits well within the expertise of the members. Success can be expected.

II. Report of Working Group on Experimental Measurements of (n,α) Cross Section Energy and Angular Distributions

Chairman: H. Vonach

Working Group Members:

M. Baba
S. Chiba
J. Csikai
A.A. Goverdovskij
R.C. Haight
N.V. Kornilov
A.B. Pashchenko

(1) Results reported at the Meeting

A considerable part of the experimental work proposed in the recommendations of the first RCM meeting (Debrecen November 1992) has been successfully completed and was reported and discussed at this meeting.

In detail the following results were achieved:

(a) α-emission from iron and its isotopes

New results for double differential α-emission cross sections of ^{56}Fe for neutron energies from threshold to 30 MeV were reported by Haight, Los Alamos, and corresponding results for natural Fe for neutron energies up to 14 MeV were presented by Baba (Tohoku University). In addition a helium accumulation measurement at En = 10 MeV was also reported by Haight. These results are in good agreement with each other and previous α-production measurements. Thus there exists now an adequate experimental data base for the neutron-induced α-production in iron.

This was demonstrated by Vonach who presented a quantitative evaluation of the ^{56}Fe(n,α) cross section showing that this is known to about 5% in the energy range between threshold and 14 MeV.

(b) Nickel and its isotopes

New measurements of double differential α-emission cross sections were reported by Baba (Tohoku University) for nat-Ni between threshold and 14 MeV, and Goverdovskij (IPPE, Obninsk) for ^{58}Ni for neutron energy up to 7 MeV. In addition new results for nat-Ni were obtained outside the CRP by Tang (Peking University, China) at 5 MeV and by Wattecamps at IRMM, Geel. Furthermore the double differential cross sections of both ^{58}Ni and ^{60}Ni have recently been measured by Haight from threshold to more than 30 MeV, which, however, still have to be analyzed.

It can be expected that (after analysis of the Los Alamos results) the experimental data for α-emission from Ni and its main isotopes ^{58}Ni and ^{60}Ni will be adequate for all applications.

(c) Chromium and its isotopes

Double differential α-emission cross sections for ^{50}Cr between threshold and 14 MeV were reported by Baba. No measurements for ^{52}Cr, the main isotope of Cr, have been performed so far due to the lack of suitable targets. Such targets, however, have recently been obtained by Vonach, who will make them available to all interested CRP members.

(d) Light elements

New measurements of double-differential α-emission cross sections for carbon and oxygen up to 30 MeV have been performed by Haight at WNR, Los Alamos. The (n,α2,3) cross sections at E = 14 MeV for above targets have been determined accurately by (n,n'γ) measurements by Hlavac (Bratislava) and measurements of the excitation functions for this reaction were performed at Los Alamos also by (n,n'γ) reactions. In addition outside of the CRP measurements of proton and deuteron production on carbon and oxygen by 40-70 MeV neutrons have been reported by Meulders from the University of Louvain, Belgium.

(e) Activation measurements

Activation cross sections for (n,α) reaction were measured for 30 nuclei at 14.7 MeV incident energy by Csikai (Debrecen University). He measured in a co-operation between Debrecen and Jülich excitation functions for $^{63}Cu(n,\alpha)^{60m}Co$ and $^{65}Cu(n,\alpha)^{62m,g}Co$ reactions over the energy range of 6-15 MeV. For the $^{63}Cu(n,\alpha)^{60m}Co$ reaction all the data between 6-12 MeV were measured for the first time except for a single value at 8.2 MeV. The excitation functions of $^{90}Zr(n,\alpha)^{87m}Sr$ and $^{94}Zr(n,\alpha)^{91}Sr$ reactions were checked on a few points between 6.8 - 14.5 MeV.

In addition high purity C, Al, $KHNO_3$, Zn, Ni, Cu, Mo, Si_3N_4 and SiO_2 samples were irradiated in Debrecen with 14.6 MeV neutrons to produce long-lived radionuclides by (n,α) reactions. The measurements of the samples activities, including the radiochemical separation are in progress.

Activation cross sections for 10 dosimetry reactions including three (n,α) reactions have been measured by Chiba in the energy range 9-12 MeV using the $H(B^{11},n)^{11}C$ reaction as neutron source.

(2) Recommendations on the future work of the CRP

The areas of the work proposed for the CRP in its first RCM were reviewed and it was agreed that these goals are still valid and should be fulfilled as completely as possible. In addition the participants agreed that the data needs for medical purposes extend to considerably higher energies ($\approx$ 250 MeV) than assumed previously and thus propose $^{12}C(n,x\alpha)$ and $^{16}O(n,x\alpha)$ studies up to this energy.

A detailed plan of the work was set up in order to achieve the objectives of the CRP in the best possible way and the following tasks were assigned to the CRP members:

(a) Structural materials:

- Haight will analyze his recent α-emission measurements on ^{58}Ni and ^{60}Ni and present the results at the next CRP meeting. He will furthermore consider more α-measurements on ^{52}Cr during his stay at Ohio University.

- Vonach will supply ^{52}Cr targets to both Baba and Goverdovskij. He will furthermore perform an evaluation of the α-production cross sections of ^{58}Ni and ^{60}Ni similar to that presented by him for ^{56}Fe at this meeting as soon as all data obtained within the CRP will become available to him.

- Baba will complete his high resolution measurements of double-differential α-emission cross sections on ^{58}Ni and start similar measurements on ^{52}Cr and possibly also on ^{nat}Cr.

- Goverdovskij will do high-resolution studies on α-emission from ^{58}Ni and start the study of α-emission on ^{52}Cr.

- Goverdovskij and Baba will jointly investigate the origin of some discrepancies between their studies of α-emission from ^{58}Ni concerning absolute cross section normalization and shapes of angular distributions.

- Goverdovskij and Kornilov will investigate the possibilities of obtaining a target of ^{53}Cr suitable for α-emission measurements, as this isotope is relatively abundant (-10%) and its (n,α) cross section can not be measured by activation.

In order to prepare for the next meeting all data on the most important reactions should be transmitted to the following CRP members as soon as they become available:

- Cr and its isotopes: N.V. Kornilov;
- Fe and its isotopes: H. Vonach;
- Ni and its isotopes: A.A. Goverdovskij;

In order to enable a detailed comparison of energy spectra and angular distributions it is highly recommended that all data reported are transformed into the CM system (channel energy). It is requested that the monitors give a status report on their reactions at the next RCM, which should contain a detailed comparison of cross sections, energy spectra and angular distributions obtained in the different experiments.

(b) Light elements:

Baba will investigate proton and deuteron emission from carbon and oxygen at high energy (40-70 MeV). Haight will analyze his measurement on ^{12}C as soon as possible and investigate the possibilities to obtain similar results for ^{16}O.

(c) Activation cross section measurements:

In order to check and improve the model calculations as well as to explain the systematics, especially the (N-Z)/A dependence of (n,α) cross sections, a number of new reliable measurements of excitation functions of such reactions from light nuclei to the Pb region will be performed; especially the reactions at 14 MeV and in some cases from threshold to 10 MeV will be measured by Csikai.

(d) Production of long lived isotopes in (n,α) reactions:

The 14 MeV cross section measurements for the reactions $^{13}C(n,\alpha)^{10}Be$, $^{17}O(n,\alpha)^{14}C$, $^{18}O(n,n'\alpha)^{14}C$, $^{39}K(n,\alpha)^{36}Cl$, $^{66}Zn(n,\alpha)^{63}Ni$ and $^{96}Mo(n,\alpha)^{93}Zr$ will be completed by measurements of the long-lived activities formed by the listed reactions in the already irradiated samples by Csikai in collaboration with other laboratories. In addition to the standard γ-spectroscopy accelerator mass spectroscopy and radio-chemical separation techniques will also be used.

(e) Study of (n,α) reactions above 14 MeV:

- Vonach will complete the analysis of his $(n,xn\gamma)$ measurements on Al (up to En = 400 MeV) and report those results relevant to the CRP at the next RCM. He will furthermore inform the members of the recently formed CRP on photon production cross sections on the data needs expressed within this CRP and specifically on the importance of further studies of $^{16}O(n,\alpha\gamma)$ reactions.

- Chiba will measure activation cross sections for important dosimetry reactions up to 30 MeV using quasi-monoenergetic neutrons from the $^{7}Li(p,n)^{7}Be$ reaction.

(f) The measurement of the (p,α) reaction is very useful to investigate α-emission from excited nuclei. Kornilov, Gurbich and Csikai have started the preparation such experiments in Debrecen.