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THE IAEA CO-ORDINATED RESEARCH PROGRAMME ON

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

STATUS REPORT

prepared at the final CRP Meeting in Sendai, Japan
25 - 29 September 1995

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

December 1996

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

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Abstract

The present report describes the results of the IAEA Co-ordinated Research Programme (CRP) on "Improvements of Measurements, Theoretical Computations and Evaluations of Neutron Induced Helium Production Cross Sections". Summarized is the progress achieved under the CRP in the following areas: measurements of α-production cross sections for structural materials; theoretical computations at (n,α) cross sections; measurements of activation cross sections; and improvement of experimental methods for (n,α) investigations. The status report gives also short summaries on the work of each laboratory which contributed to the results of the CRP.

Attached is the list of program members and participants of CRP meetings.

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

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Foreword

This report summarizes the work performed by participants in the IAEA Co-ordinated Research Programme (CRP) on "Improvements of Measurements, Theoretical Computations and Evaluations of Neutron Induced Helium Production Cross Sections". This project was organized by the IAEA Nuclear Data Section with the purpose to improve our knowledge of neutron-induced helium production cross sections in general and to provide reliable data (experimental and evaluated) for the important structural materials, especially for Cr, Fe and Ni, where better data are needed for fusion reactor technology. Participants of ten laboratories from seven countries joined in this task.

Within the framework of an international co-operative effort, the CRP participants performed a number of highly precise measurements and calculations of the required data. They have also contributed to the development of methodology and measurement techniques, and stimulated a number of measurements and evaluations in laboratories not directly involved in the IAEA project.

The establishment of the CRP has spawned several new interlaboratory collaborations (Tohoku-Obninsk-JAERI; Los Alamos-Vienna) and strengthened existing relationships (Jülich-Debrecen; Debrecen-Obninsk-Havana; Oak Ridge-Obninsk). 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.

The CRP has been successful towards the goal of providing an improved data base of neutron induced He-production data for fusion reactor technology and other applications. The results of the work undertaken by the CRP are presented in Parts II, III, IV and V of this report. Part II describes the status of improved cross section data for main structural materials. The CRP has provided He-production cross sections for iron with very much reduced uncertainties, which now satisfy the needs for all applications. A summary of performed activation measurements is given in Part III, including data that originate from sources other than the CRP. Progress achieved in theoretical computations and in experimental technique for investigation of (n,α) reactions are reported in Parts IV and V, respectively.

The status report collects also short summaries on results of the work for each laboratory which contributed to the project.

Although the main part of the work plan of the CRP has been fulfilled successfully, some further work is required for the following reasons:

- A number of experiments started within the CRP has not been completely analyzed by the time of the final CRP meeting;

- For one of the important structural materials, chromium, no measurement for the main isotope ^{52}Cr has been performed because of technical difficulties in obtaining suitable targets;

- New requests for He-production data in materials emerged since the start of the CRP like the need for He-production data in silicon for the semi-conductor industry.

In detail, the recommendations of the final CRP meeting for the future work after formal completion of the programme are addressed in report INDC(NDS)-353, September 1996.

Vienna, November 1996 — Anatoly B. Pashchenko

THE IAEA COORDINATED RESEARCH PROGRAM ON "IMPROVEMENTS OF MEASUREMENTS, THEORETICAL COMPUTATIONS AND EVALUATIONS OF NEUTRON INDUCED HELIUM PRODUCTION CROSS SECTIONS"

Status Report of the CRP to the IAEA

Prepared at the final CRP meeting in Sendai, Japan, 25-29 September 1995

I. EXECUTIVE SUMMARY

H.K. Vonach, G.J. Csikai, A.B. Pashchenko

At the 1986 Gaussig Advisory Group Meeting on Nuclear Data for Fusion Reactor Technology [1] it was recommended to create an international evaluated nuclear data library for this purpose. In the process of selecting evaluated nuclear data files for this library it turned out that even the most recent evaluations (ENDF/B-VI, JENDL-3, EFF-2, BROND-2) showed large discrepancies up to a factor of two for the (n,α) cross sections in the neutron energy region "threshold - 14 MeV" and that only very few and discrepant experimental data existed for neutron energies below 14 MeV.

In order to improve this situation a Coordinated Research Program (CRP) was initiated by the IAEA Nuclear Data Section with the following objectives:

- Improvement of the experimental data base for $(n,x\alpha)$ cross sections between threshold and 14 MeV, especially for the structural materials Cr, Fe and Ni and their main isotopes;

- Improvement of the theoretical models and their parametrizations for the computation of $(n,x\alpha)$ data, especially investigation of the causes of the existing discrepancies;

- Improvement of the existing $(n,x\alpha)$ data evaluations, especially for the structural materials.

For this purpose the IAEA succeeded in obtaining the participation of ten laboratories from seven countries (Institute of Atomic Energy, Beijing, China; Center of Applied Studies for Nuclear Development, Havana, Cuba; Kossuth University, Debrecen, Hungary; Japan Atomic Energy Research Institute and Tohoku University, Japan; Institute of Physics and Power Engineering and Institute of Nuclear Power Engineering, Obninsk, Russia; Oak Ridge National Laboratory and Los Alamos National Laboratory, U.S.A., and Institut für Radiumforschung und Kernphysik, University of Vienna, Austria). In addition scientists from Tohoku University, Kyushu University and Data Engineering Incorporation, Japan, Institute for Reference Materials and Measurements, Geel, Belgium, the Slovak Academy of Science, Bratislava, and the Institute of Atomic Physics, Bucharest, Romania, joined the program on a more informal basis.

The major activities of the CRP were performed by individual participants at their home institutes. Periodically the IAEA convened CRP meetings, bringing together all participants to review the status of the activities of the CRP. Between meetings, participants informed the IAEA of all relevant work on the subject and sent copies of all papers, progress reports, etc., to the IAEA, which were distributed to all participants. At least once a year, each participant submitted a progress report to the IAEA.

A first Research Coordination Meeting (RCM) of this CRP was held at Debrecen, Hungary, in November 1992 [2] and the second meeting was organized in Beijing, China, in November 1994 [3]. A number of important results have already been reported at those meetings and the participants agreed on a detailed plan for their future work. The intermediate results of the CRP were reported at the International Conference on Nuclear Data for Science and Technology in Gatlinburg, May 9-13, 1994 [4]. The third and final CRP meeting was hosted by Tohoku University and held in Sendai, Japan, from 25 to 29 September 1995, where the Status Report of the CRP members to the IAEA was prepared, which is given below. The report summarizes the progress achieved by the CRP as whole in four sections: measurements of α-production cross sections of structural materials; theoretical computations of (n,α) cross sections; measurements of activation cross sections; and improvement of experimental methods for (n,α) investigations. In addition, it gives a short summary of the activity of each laboratory participating in the CRP and those observers who contributed significantly to the work of the programme. Details about these topics are given in publications which are also listed in this status report.

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4. H. Vonach, S. Chiba, A.B. Pashchenko, "Report on the IAEA Coordinated Research Program on "Improvements of Measurements, Theoretical Computations and Evaluations of Neutron Induced Helium Production Cross Sections", In: Proceedings of the Int. Conf. on Nuclear Data for Science and Technology, Gatlinburg, May 9-13, 1994, J.K. Dickens (ed.) Vol. 2, p. 925.

II. STATUS OF THE He-PRODUCTION CROSS SECTIONS FOR THE STRUCTURAL MATERIALS Cr, Fe and Ni

H.K. Vonach, M. Baba, S. Chiba, G.J. Csikai, R.C. Haight, S. Iwasaki, N.V. Kornilov, Y. Takao, E. Wattecamps

(1) *Iron and its Isotopes*

Measurements of double-differential α-emission cross sections for the ^{56}Fe, the main isotope of iron, have been performed by R. Haight et.al., Los Alamos, from threshold to 30 MeV and corresponding results for natural iron for neutron energies from threshold to 14 MeV were presented by M. Baba, Tohoku University. In addition, a helium accumulation measurement at $E_n = 10$ MeV was also reported by R. Haight. All these measurements agree within experimental uncertainties with each other and also with previous Geel measurements. Thus there exists now an adequate experimental data base for the neutron induced α-production on ^{56}Fe.

This was demonstrated at RCM-2 by H. Vonach, IRK, Vienna, who performed a quantitative evaluation of the α-emission cross section of ^{56}Fe from threshold to 20 MeV. This evaluation, which has been performed with the code GLUCS based on Bayes theorem, showed that the total α-emission cross sections of ^{56}Fe is now known to about 5% from threshold to 14 MeV. The result of this evaluation given in Table 1 below is recommended to be adopted for this cross section.

Table 1: Recommended values for the α-production cross sections of ^{56}Fe

Neutron energy (MeV)	Cross section (mb)
4.25	0.031 ± 0.025
4.75	0.126 ± 0.061
5.25	0.50 ± 0.09
5.75	1.59 ± 0.14
6.25	3.79 ± 0.25
6.75	6.08 ± 0.36
7.25	8.68 ± 0.48
7.75	11.27 ± 0.61
8.25	13.13 ± 0.72
8.75	16.11 ± 0.85
9.25	18.03 ± 0.93
9.75	21.67 ± 1.07
10.25	23.22 ± 1.20
10.75	25.24 ± 1.58
11.25	29.18 ± 1.83

Table 1: Recommended values for the α-production cross sections of ^{56}Fe (cont'd)

Neutron energy (MeV)	Cross section (mb)
11.75	31.12 ± 1.95
12.25	33.94 ± 1.97
12.75	35.82 ± 2.09
13.25	39.98 ± 2.37
13.75	40.11 ± 2.17
14.25	43.10 ± 1.66
14.75	45.36 ± 1.71
15.50	48.26 ± 2.80
16.50	50.42 ± 3.54
17.50	54.35 ± 4.47
18.50	60.50 ± 5.72
19.50	65.46 ± 6.92

The α-emission cross sections for the minor isotopes of Fe still do have large uncertainties but due to their low abundance, this has only a small influence on (n,α) cross sections for ^{nat}Fe. Thus also the α-emission cross sections for ^{nat}Fe can be obtained with an accuracy of ~5% by combining Vonach's evaluation with the ENDF/B-VI or JENDL-3 results for the minor isotopes.

(2) *Nickel and its Isotopes*

Double-differential α-emission cross sections for ^{58}Ni and ^{60}Ni from threshold to 30 MeV have been measured by R. Haight et.al. at Los Alamos and for several energies in the 4.5-11.5 MeV range by M. Baba et.al., Tohoku University. Preliminary values of the total α-production cross sections from both experiments have been presented at this meeting. Measurements of double differential cross sections for natural nickel have also been performed from threshold to 14 MeV by M. Baba et.al. and for ^{58}Ni from 3 to 7 MeV by A. Goverdovski et.al., Obninsk, and were already reported at the last CRP meeting as well as He-accumulation measurements at 10 MeV for ^{58}Ni, ^{60}Ni, ^{61}Ni, and ^{nat}Ni by R. Haight et.al., which have also been presented at the RCM-2. In addition outside of the CRP new measurements on ^{58}Ni were obtained by G. Tang et.al., Peking University, at 5 MeV and by E. Wattecamps et.al., IRMM, Geel, from threshold to 14 MeV.

All these measurements, obtained by the use of quite different experimental methods agree within experimental uncertainties with one small exception. In the neutron energy region around 5 MeV A. Goverdovski's cross sections are considerably smaller than those from all other groups (Haight, Baba, Wattecamps, Tang). The reason for this discrepancy has not yet been identified.

Summarizing the data situation it can be stated that the data for the total α-emission cross sections for ^{nat}Ni and its main isotopes now also seem to be adequate. It can be expected that an evaluation similar to that performed for ^{56}Fe will also result in evaluated cross sections with uncertainties around 5% at least up to a neutron energy of 14 MeV.

This evaluation, however, will have to wait for the availability of the final cross sections from the Los Alamos and Tohoku experiments. Up to that time it is recommended to use the recent calculations by N. Yamamuro.

(3) *Chromium and its Isotopes*

Because of the difficulties to produce isotopically enriched chromium targets, no measurements could be performed for ^{52}Cr, the main isotope of Cr. Only for ^{50}Cr (abundance 5%) measurements have been performed for several energies from threshold to 14 MeV by M. Baba et.al. Apart from these results there exists one double-differential α-emission cross section measurement for ^{nat}Cr for neutron energies from threshold to 10 MeV from A. Paulsen and at 14 MeV on ^{nat}Cr from E. Wattecamps. There are measurements also at 14 MeV on ^{50}Cr from S. Grimes and from G. Dolya and on ^{52}Cr from S. Grimes. The rather old measurement from IRMM, Geel, however, have been indirectly confirmed by the CRP work on Fe and Ni. The Geel measurements on ^{nat}Fe and ^{nat}Ni which were performed in the same experiment as ^{nat}Cr have been definitely confirmed by all the CRP work on these elements. Thus it can be assumed that the old IRMM data on ^{nat}Cr are correct and the choice of evaluation should be based on the agreement with these data and the 14 MeV data of S. Grimes, and G. Dolya for ^{50}Cr and ^{52}Cr. Accordingly it is also recommended to use the results of N. Yamamuro presented at this meeting until more experimental data on ^{52}Cr or ^{nat}Cr become available.

III. SUMMARY OF PERFORMED ACTIVATION MEASUREMENTS

G.J. Csikai

In order to check and improve the model calculations as well as to explain the systematics, especially the (N-Z)/A and isotopic dependences of (n,α) cross sections, new reliable data were obtained for 33 nuclei at (14.7$\pm$0.1) MeV incident energy by G. Csikai et.al., Debrecen University, Hungary, and Y. Ikeda et.al., JAERI, Japan. Activation cross sections for $^{51}V(n,n\alpha)^{47}Sc$, $^{78}Se(n,\alpha)^{75m}Ge$, $^{80}Se(n,\alpha)^{77m}Ge$, $^{114}Cd(n,\alpha)^{111m}Pd$, $^{118}Sn(n,\alpha)^{115g}Cd$ and $^{203}Tl(n,\alpha)^{200g}Au$ reactions were measured in Debrecen for the first time. On the basis of these consistent data a new empirical relation was given for the description of the isotopic dependence of $\sigma_{n,\alpha}$ values in the 14 MeV range. New $\sigma_{n,\alpha}$ data were measured in the 14 MeV region at JAERI FNS for ^{17}O, ^{19}F, ^{23}Na, ^{35}Cl, ^{37}Cl, ^{55}Mn, $^{89}Y(n,\alpha)^{86m}Rb$ and $\sigma_{n,n\alpha}$ for ^{18}O.

Measurements of the (n,α) activation cross sections were performed for a number of fusion and dosimetry related materials from threshold to 20 MeV. The (n,α) cross sections of ^{51}V, ^{59}Co and ^{93}Nb have been determined in the 9-12 MeV range at JAERI Tandem facility using the $^{1}H(^{11}B,n)^{11}C$ reaction for the production of mono-energetic neutrons.

Systematic measurements were carried out by S. Iwasaki et.al. at Tohoku University, Japan, for 23 threshold reactions below 6 MeV and between 12-20 MeV. Alpha emission activation cross sections were measured for the following reactions: $^{27}Al(n,\alpha)^{24}Na$, $^{59}Co(n,\alpha)^{56}Mn$, $^{58}Ni(n,p\alpha)^{54}Mn$ and $^{93}Nb(n,\alpha)^{90m}Y$. Integral test of (n,α) activation cross sections using thick Li+d broad energy neutron field for Al, Co and Cu was also performed.

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 have been measured. 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 $^{90}Zr(n,\alpha)^{87m}Sr$, $^{94}Zr(n,\alpha)^{91}Sr$, $^{51}V(n,\alpha)^{48}Sc$, $^{92}Mo(n,\alpha)^{89m,g}Zr$ and $^{89}Y(n,\alpha)^{86}Rb$ reactions were checked on a few points between 6.8 and 14.0 MeV range using the MGC-20 (Debrecen) and CV 28 (Jülich) variable energy cyclotrons.

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 cross sections by AMS method are in progress for the $^{13}C(n,\alpha)^{10}Be$, $^{17}O(n,\alpha)^{14}C$, $^{18}O(n,n\alpha)^{14}C$ and $^{39}K(n,\alpha)^{36}Cl$ reactions.

Determination of spectrum-averaged (n,α) activation cross sections for thick target Be+d neutrons at 9.8 MeV incident deuteron energy is in progress in Debrecen for the following nuclei: ^{51}V, ^{54}Fe, ^{59}Co, ^{68}Zn, ^{93}Nb, ^{90}Zr, ^{94}Zr and ^{92}Mo.

IV. PROGRESS IN THEORETICAL COMPUTATIONS OF He-PRODUCTION CROSS SECTIONS

C.Y. Fu, R. Capote Noy, A.B. Pashchenko, N. Yamamuro, A.V. Zelenetskij, J. Zhang

(1) *Summary of Achievements*

The working group on computations and evaluations concluded that the most serious problem in accurately predicting the (n,α) cross section was in the 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 research program is related to nuclear level densities.

The Gilbert-Cameron (GC), Generalized Superfluid Model (GSM) and Back-Shifted Fermi Gas (BSFG) formulas for nuclear level densities, equally popular among evaluators, differ in excitation energy dependence (shape). By forcing agreement of these three level densities at two selected energies, the shape effects on calculated (n,α) cross sections and α-emission spectra can be examined. C.Y. 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.

R. Capote performed combinatorial calculations (CC) of the total level densities (with vibrational enhancement added for RCM-3 to improve the CC accuracy) to impose constraints on the level densities of residual nuclei not having experimental neutron resonance information. This lack of level density information is true for ^{58}Ni and ^{58}Co, the two major residual nuclei in the ^{58}Ni cross-section calculation. To use the CC results in cross-section calculations, R. Capote derived BSFG parameters by fitting the discrete levels and the CC result near the neutron binding energy. To study the BSFG and GSM differences, A. Zelenetskij did the same fitting of CC using GSM. The differences in the calculated cross sections using BSFG and GSM reflect the shape differences between BSFG and GSM. This result of BSFG and GSM differences is consistent with that shown above by C.Y. Fu. The CC-GSM combination appears to be a useful tool for cross section calculations since a good description of (n,2n), (n,p) and (n,α) cross sections was achieved without level density adjustments.

The above approach by R. Capote and A. Zelenetskij has also been applied for ^{56}Fe. In this case, the uncertainties in the level densities are smaller because two of the residual nuclei have neutron resonance information. This smaller uncertainty allows optical model problems in the alpha particle channel to be addressed. A. Zelenetskij and R. Capote found that the agreement of their calculations with experimental data obtained in this CRP can be improved by increasing the diffuseness in the optical model parameters for alpha particles.

N. Yamamuro calculated (n,α) and α-production cross sections for Cr, Fe and Ni, as well as their major isotopes up to 50 MeV. He is able to obtain very good agreement with data. This success is attributed to the use of A. Ignatyuk type of shell corrections in the GC formalism and the freedom to adjust the diffuseness parameter in the optical model for α particles. The level density parameter a is also allowed to be adjusted. He hopes that systematics for the diffuseness parameters can be established.

J. Zhang has improved his UNF code in several major areas. First, the master equation formulation of the pre-equilibrium model used in his code now conserves angular momentum and parity. This conservation is then utilized to improve the Iwamoto pickup model in such a way that angular distributions in complex particle emissions can be obtained in a natural manner. Validity of this model has been established by comparisons with experimental double differential (n,α) cross sections for V, Fe, Nb and Bi.

(2) *Conclusions and Recommendations*

A brief summary of achievements by each participant of the CRP is included in this report. It is obvious that a large amount of calculations have been carried out for understanding the problems in computing helium-production cross sections. In the mean time, some applications of the calculational techniques have been made, such as the generation of the ADL-3 activation library by A. Zelenetskij and his colleagues.

Although the CRP has concluded, work continues. Some recommended research to continue is given below.

N. Yamamuro has used the GSM shell correction in the GC formalism in order to achieve good agreement with experimental data up to 50 MeV. Let us call this level density approach GCY. During the Sendai meeting, GCY has been compared with GC, BSFG, and GSM for their shape differences for ^{58}Ni up to 20 MeV. The spread of the level densities is a factor of 2 near 20 MeV where GCY yields the highest level density, GC the second, GSM the third, and BSFG the lowest. To determine which of the 4 formalisms is the most suitable for cross section calculations up to 50 MeV remains an interesting and challenging task. This task is strongly recommended for anyone interested.

In N. Yamamuro's presentation, only calculated cross sections using GCY were shown. It is recommended that he shows two calculated cross section curves, using GCY and GC, to quantify their effects on calculated cross sections.

R. Capote and A. Zelenetskij have been successful in using CC results as constraints of level densities for residual nuclei not having neutron resonance information required for the ^{56}Fe and ^{58}Ni cross section calculations. It is recommended that they validate their method for other mass regions such as mass 100 and mass 200.

J. Zhang has been working on double differential cross sections for charged particle emission for incident neutron energy of 14 MeV. It is recommended that he compares his UNF calculations with helium-production data obtained at this CRP with emphasis on Cr, Fe and Ni as well as their major isotopes. Since J. Zhang uses BSFG, it would be very useful to add a second level density option to study level density effects. This recommendation of using two level density formalisms is based on the observation that many level density problems at 14 MeV and higher energies have been hidden under an arbitrary pre-equilibrium model parameter.

V. Avrigeanu (an observer at RCM-1) has been using an energy-dependent single-particle state density as a means to obtain better cross section fit at energies above 14 MeV. It would be interesting to find out whether his approach is in effect a compensation of the low level density at high energies due to the use of BSFG and/or a simulation of the diminishing shell correction (increasing level density) at high energies in the GSM.

Problems in the optical model parameters are well known. However, the problems are not easy to solve because deficiencies in the optical model tend to be hidden under the shadow of the level density uncertainties. This fact is the most serious in the case of (n,α) cross section calculation because this cross section is not only proportional to the level density in the (n,α) channel, but also very sensitive to level density uncertainties in the (n,n') and (n,p) channels. N. Yamamuro, as well as R. Capote and A. Zelenetskij could adjust the optical model diffuseness in the alpha channel only after the required level densities have been determined, sometimes with large effort, for individual cases.

During the course of this CRP, the members in the theoretical group have cooperated with one another and learned from one another. The joint achievement is definitely larger than possible individually. The participants of the computational group all appreciate the IAEA's organization of this CRP.

V. PROGRESS IN EXPERIMENTAL TECHNIQUE FOR INVESTIGATION OF (n,α) REACTION

H.K. Vonach, M. Baba, R.C. Haight, N.V. Kornilov

Advances in experimental techniques in the measurement of double differential cross section for neutron-induced α-particle production include the greatly extended utilization of gridded ionization chamber and the implementation of new monoenergetic neutron sources and a spallation white neutron source.

α-spectrometers on the basis of Gridded Ionization Chamber (GIC) were developed at IPPE (Russia) [1] and Tohoku University (Japan) [2] for use at the neutron energy range up to 14 MeV during this CRP. The GIC is a very powerful tool for measurement of angular distribution of the reaction products. This device has some advantages in comparison with formerly used ones:

(a) The GIC has rather good energy resolution (~50-70 keV) to measure cross sections for separate α-groups.
(b) Due to the large solid (~4π) angle the GIC has high counting efficiency, which permits to use thin targets ~300 $\mu g/cm^2$.

A schematic diagram of the GIC is shown in Fig. 1. It achieves low background and high stopping power by employing high Z elements for electrodes, other chamber materials (Ta, W) and the counting gas (Kr or Xe). The sample foils under investigation are placed on the cathode plate and bombarded by a collimated neutron beam. Self-supporting foils (~2 mg/cm^2) and foils prepared by vacuum evaporation (~300 $\mu g/cm^2$) are used in the experiments. α-particles from the sample are detected in almost 4π geometry (or 2π geometry). For optimum separation of α-particles from protons, the pressure of the counting gas is adjusted so as to make the range of α-particles slightly shorter than the cathode-grid distance.

Three signals from the common cathode and two anodes are gathered as two sets of two-dimensional data. The anode and cathode signals of GIC, P_a and P_c, are given by the following equations, respectively, provided that α-particles from the sample are stopped by the counting gas before reaching the grid:

$$P_a = C_a.E(1+\sigma-\sigma\ (\bar{x}/d)\ \cos\theta) \approx C_a.E \qquad (1)$$

$$P_c = C_c . E(1 - (\bar{x}/d) \cos\theta) \qquad (2)$$

where, E is α-energy, d - the cathode-grid distance, θ - the emission angle, σ - the grid inefficiency (3-6%), C_a and C_c - the amplification factors, and $\bar{x}$ is the distance from the cathode to the center-of-gravity of the ionization track. Background-subtracted two-dimensional data for P_a *vs* P_c are transformed into DDX according to eqs. (1) and (2).

The DDX data are corrected for a) geometrical efficiency of GIC, b) background due to (n,p) reactions and contributions of background neutrons, c) energy loss within the sample, and d) (n,α) reaction kinematics. The neutron flux is determined relative to ^{238}U(n,f) [1] and H(n,n) [2,3] reactions.

Figure. 2 illustrates α-particle spectra of Ni from high-resolution measurements. The α-particles for each state of the residual nucleus, ^{55}Fe, are clearly separated from each other. These data indicate the main advantage of the GIC for α-emission reaction investigations.

The $^{14}N(d,n)^{15}O$, $^{15}N(d,n)^{16}O$ and $^{1}H(^{11}B,n)^{11}C$ reactions were successfully used to produce (quasi-) mono-energetic neutrons to measure the (n,xα) cross sections in the "missing" energy region of 7 to 12 MeV: The ^{14}N+d and ^{15}N+d reactions, available at Tohoku University [4], were used by M. Baba to obtain double-differential (n,xα) cross section of Ni, Fe, Cr and Cu at 7.6 MeV and 11.5 MeV, respectively. The $^{1}H(^{11}B,n)^{11}C$ reaction available at JAERI tandem [5] was used to measure the (n,α) cross sections of ^{51}V, ^{59}Co and ^{93}Nb at energies of 9.1, 10.1, 11.1 and 11.8 MeV. These neutron sources were proved to provide unique neutron fields to investigate various neutron induced reactions in the energy region at which the data are extremely rare.

The spallation neutron source at Los Alamos (LAMPF/WNR/LANSCE) [6] has been utilized in the CRP to provide (n,xα) DDX data over the continuous neutron energy range from threshold to 50 MeV. This source is based on the interaction of an 800 MeV proton beam from LAMPF with a tungsten target to produce a spectrum of neutrons from less than 1 MeV to several hundred MeV. With the presently used production angle of 90°, sufficient neutrons are produced up to 50 MeV for (n,xα) studies [7].

Neutron energies are identified by time of flight techniques over a flight path of 9 meters and the energy resolution is limited only by the time spread of the neutron source (~ 1 ns) and the time resolution of the detectors. Because all neutron energies in the useful range are on an equal footing, this source is particularly useful for filling in the 10-13 MeV region, difficult to address with monoenergetic neutron sources, and for expanding our knowledge well beyond 17 MeV. The intensity and availability of this source have improved markedly in the past two years.

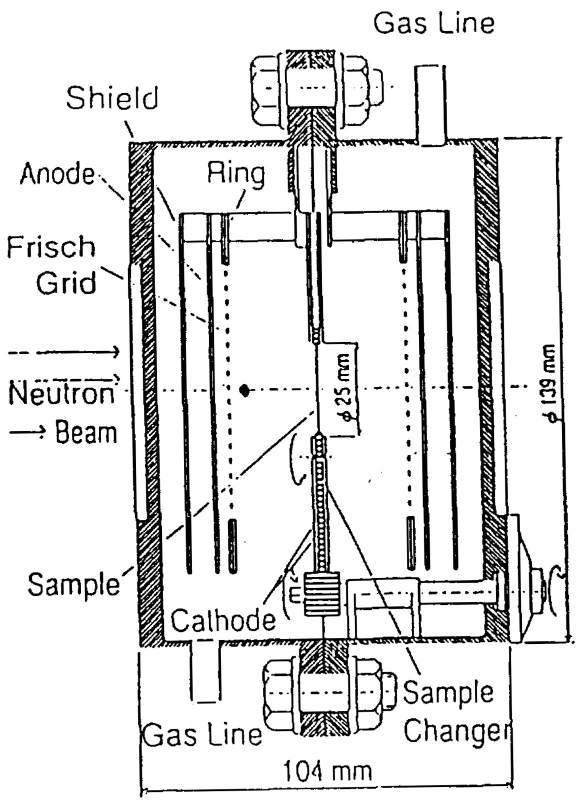

Fig.1 Schematic view of the ionization chamber

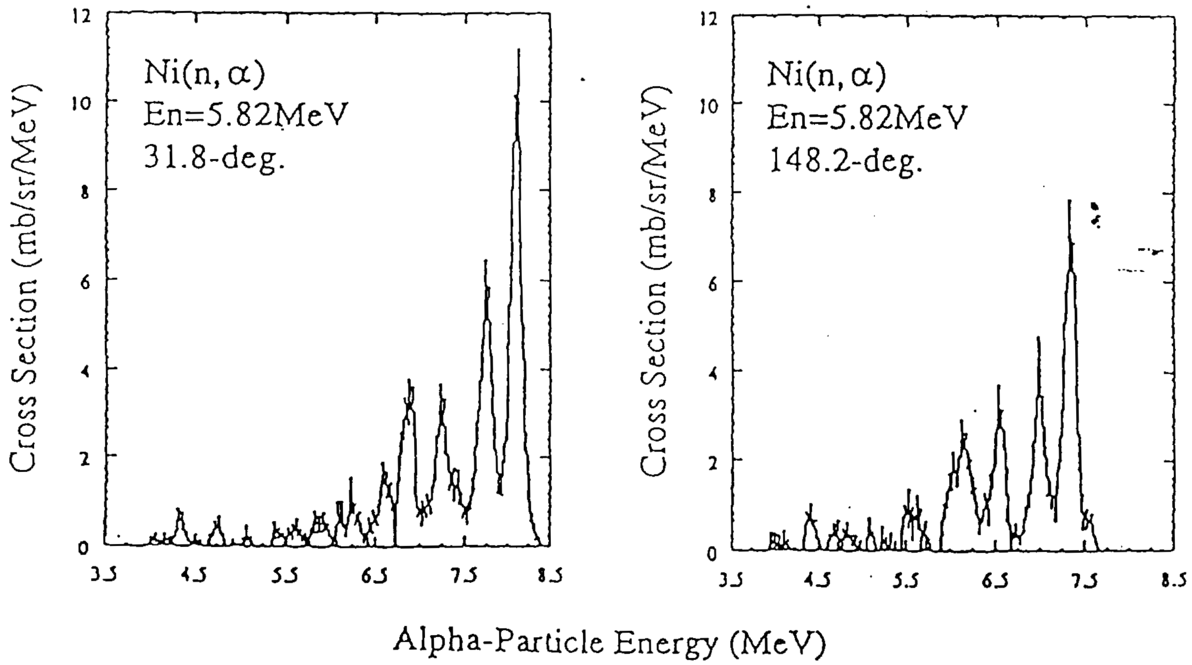

Fig.2 High resolution α-emission spectra of Ni.

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Attachment 1

Co-ordinated Research Programme

"Improvement of Measurements, Theoretical Computations and Evaluations of Neutron Induced Helium Production Cross Sections"

Scientific Secretary: Anatoly B. PASHCHENKO

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Attachment 2

SUMMARY REPORTS

Brief summaries of the activity of each laboratory participating in the CRP and those observers who contributed to the work of the IAEA-sponsored programme are given below.

SUMMARY OF THE WORK PERFORMED UNDER RESEARCH AGREEMENT 6876/CF

CRP on "Improvement of measurements, theoretical computations and evaluations of neutron induced helium-production cross sections"

Institute für Radiumforschung und Kernphysik
Universität Wien
Chief Scientific Investigator: H.K. Vonach

Within the CRP the following work was performed:

1. Measurements of the double-differential α-emission cross sections and total α-emission cross sections from threshold to more than 20 MeV at the WNR-facility at Los Alamos (in co-operation with R.C. Haight, Los Alamos) for the following nuclei: ^{10}N, C, O, ^{27}Al, Si, ^{51}V, ^{56}Fe, ^{59}Co, $^{58,60}Ni$. A large part of these data has still to be analyzed [1-5].

2. Measurement of the total α-production cross section of ^{nat}Fe, ^{56}Fe, ^{nat}Ni, ^{58}Ni, ^{60}Ni and ^{nat}Cr at E_n = 10 MeV by means of He-accumulation (in cooperation with R.C. Haight, Los Alamos). This work has been completed, an article has been submitted to Nucl. Science and Engineering [6,7].

3. Measurements of the double-differential α-emission cross section of ^{58}Ni for E_n = 3.5 - 7 MeV using the method of gridded ionization chamber at IPPE, Obninsk (in cooperation with A. Goverdovski) [8].

4. Evaluation of the total α-emission cross section of ^{56}Fe from threshold to 20 MeV including complete covariance information. This work has been completed and published [9-10].

WORK PLANNED AFTER THE FORMAL END OF THE CRP

1. Completion of the analysis of the double-differential neutron emission cross section measurements performed at WNR, Los Alamos, publication of the results and transfer of the data to NNDC, Brookhaven, to be included in EXFOR.

2. Evaluation of the total α-emission cross sections of ^{58}Ni and ^{60}Ni after completion of the analysis of the WNR, Los Alamos, and Tohoku University data.

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SUMMARY OF THE RESULTS ACHIEVED UNDER CRP ON "IMPROVEMENT OF MEASUREMENTS, THEORETICAL COMPUTATIONS AND EVALUATIONS OF NEUTRON INDUCED HELIUM PRODUCTION CROSS SECTIONS" RESEARCH CONTRACT 7048/RB

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The master equation theory of precompound and compound nuclear reactions has been generalized to include the conservation of angular momentum and parity [1]. This is achieved by taking into account spin- and parity- dependent lifetimes of occupation probabilities. Based on this improved theory, the UNF code system has been developed as a tool for calculating nuclear reaction cross sections and double differential cross sections at incident energies below 20 MeV [2]. This code is further improved by adding pick-up mechanism for composite particle emissions [3,4]. A method to calculate double differential cross sections for α-particle emission [5] based on the leading particle model and the pick-up mechanism was reported at the first CRP meeting in Debrecen. The auxiliary plotting code UNFTOOLS was developed. As reported at the 2nd RCM meeting in Beijing, the code can plot curves of cross section, spectra and double differential cross section directly from the UNF output files. The code can also plot experimental data and data in ENDF-6 format simultaneously.

The conclusions reported at the 3rd RCM meeting in Sendai are as follows.

- If using the direct reaction theory to describe α-particle emission, the knock-out mechanism and the three nucleon transfer mechanism contribute very small value of He-production cross sections. In general the calculated value is on one or two order of magnitude lower than experimental data.

- In previous exciton model calculations, α-particle emission from pre-equilibrium states must be started at exciton state n=7, in which four nucleons are above the Fermi surface. In this case the α-particle emission rate is already very small, so it could not reproduce experimental data.

- The pick-up mechanism in pre-equilibrium reaction processes plays very important role for He-production. The configuration {1,3} (one particle above the Fermi surface pickes-up three nucleons below the Fermi surface) is the dominant part. In this way the α-particle emission can be started at n=3 exciton state. Iwamoto model is employed to account for the pick-up mechanism. The results show great improvement.

- The further study found that the formation factors calculated by Iwamoto model overestimate the formation probabilities. If the excitation energy restriction on the momentum space integration is taken into account, then the formation probabilities are reduced and the pick-up factors become E-dependent. The double differential cross sections of composite emission calculated by UNF code for ^{56}Fe and ^{59}V give very good fitting as shown at the 3rd RCM meeting in Sendai.

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SUMMARY OF THE RESULTS ACHIEVED UNDER RESEARCH CONTRACT 7049/RB

CRP on

"IMPROVEMENTS ON MEASUREMENTS,THEORETICAL COMPUTATIONS AND EVALUATIONS OF NEUTRON INDUCED HELIUM PRODUCTION CROSS SECTIONS"

Center of Applied Studies for Nuclear Development, Havana, Cuba
Chief Scientific Investigator: Roberto Capote Noy
May 1992 - September 1995

During the time period covered by this CRP the following results were obtained:

1. Closed formulas for one and two quasiparticle state densities were derived. Analytical results were tested against exact combinatorial calculation in the framework of the BCS theory, using equidistant shell model spectra. Relationship between particle-hole and quasi-particle state densities was established (presented at the 1st RCM).

2. Preequilibrium exciton model code to calculate particle and gamma ray emission, including composite particle emission (pick-up contribution) was developed and tested against experimental data (presented at the 1st RCM).

3. Combinatorial calculations (CC) of the total level density for Co-58, Ni-58 and Fe-58 using shell spectra as the input were carried out. Pairing interaction was considered in this calculation in the framework of the BCS theory. The results were compared with the Generalized Superfluid Model (GSM) and Back-Shifted Fermi Gas Model (BSFGM) parameterizations. Except for Co-58, the absolute magnitude of the all results were in good agreement with the combinatorial calculations (presented at the 2nd RCM).

4. Cross sections and emission spectra for Ni-58 neutron induced reactions were calculated in the energy range up to 20 MeV, using BSFGM for level density description. Calculated (n,α) cross section underestimated experimental data in the energy range below 14 MeV (presented at the 2nd RCM).

5. Combinatorial calculations of the total level density for Co-58, Ni-58, Fe-55, Fe-56, Mn-56 and Cr-53 were carried out. Additionally, vibrational enhancement of the calculated intrinsic level densities was considered. Results of the CC were used to determine high energy behaviour of the phenomenological parameterizations (GSM & BSFGM) for nuclei not having experimental resonance information (presented at the 3rd RCM).

6. For neutrons incident on Fe-56 and Ni-58 nuclei excitation functions of (n,2n), (n,np+pn), (n,p), (n,α)and (n,αn+nα) reactions as well as helium and hydrogen production cross sections were calculated for neutron energies up to 20 MeV. BSFGM & GSM parameters were fixed according to the results of combinatorial calculations. An effective reduction of Coulomb barrier for alpha particles seems to be needed in order to describe (n,α) experimental data on Ni-58 and Fe-56 nuclei (presented at the 3rd RCM).

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7. "Nuclear level densities and optical model parameters in helium production cross section calculations on Fe-56 and Ni-58", 3rd IAEA RCM of the CRP, Sendai, Japan, 25-29 Sept. 1995

MEASURED, ESTIMATED AND CALCULATED (n,xα) REACTION CROSS SECTIONS*

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**Research Contract 6971/R1/RB*
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Activation cross-sections have been measured for 33 (n,α) reactions in the 14 MeV range. The systematics in the $\sigma_{n,\alpha}$ data for isotopic dependence could be improved [1-4]. Data for 6 reactions were measured for the first time. New estimated data are given for the production of long-lived isotopes and for the total $\sigma_{n,\alpha}$, values of some elements at (14.1±0.1) MeV using the empirical $\sigma_{n,\alpha}(A)$ function and the isotopic abundance. Data for 19 elements and 26 isotopes have been estimated. Among these there are 6 long-lived $\alpha_{n,\alpha}$ reaction products. The $\sigma_{n,\alpha}$ values for elements and isotopes were compared with the available He emission data.

Cross sections of the ^{63}Cu(n,α)^{60}Co^{m} and ^{65}Cu(n,α)^{62}Co^{m,g} reactions were measured over the 6-14 MeV range and compared with the STAPRE calculations. The cross section data in the 6.8-13.9 MeV range were measured for (n,α) reactions on ^{51}V, ^{90}Zr, ^{94}Zr, ^{92}Mo and ^{89}Y target nuclei. The STAPRE calculations could not reproduce the $\sigma_{n,\alpha}(E)$ and $\sigma^{m}/\sigma^{g}(E)$ functions in the 11-13 MeV range [9,11].

Spectra of ^{252}Cf, Pu-Be, ^{9}Be(d,n) and D-T neutrons traversing slabs of different materials have been determined to produce benchmark fields for testing and validating of the differential data. Determination of spectrum averaged $\sigma_{n,\alpha}$ data for V, Fe, Co, Zn, Nb, Zr and Mo samples are in progress [10].

The signal-to-background ratio was improved for the D_2 gas cell neutron source to increase the precision of the measured cross sections [5,6,7,8].

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Summary of JAERI's contribution to the IAEA CRP on

"Improvement of Measurements, Theoretical Computations and Evaluations of Neutron Induced Helium Production Cross Sections"

Research Agreement 7050/CF
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Abstract

Contributions of JAERI (Japan Atomic Energy Research Institute) to IAEA CRP on "Improvement of Measurements, Theoretical Computations and Evaluations of Neutron Induced Helium Production Cross Sections" are summarized. Three different kinds of activities were carried out: 1) the double-differential cross section measurements at 7 to 11 MeV region, 2) the activation cross section measurement at 9 to 12 MeV, and 3) the activation cross section measurement of light mass nuclei around 14 MeV.

Chronological summary

Our main effort was put into the energy region of 7 to 12 MeV, where experimental (n,xα) data are specifically scarce. In the last years, however, experiments were also carried out at 14 MeV and 20 to 30 MeV region.

In the period of 1991 to 1992, we have been working closely with the group of M. Baba, Tohoku University, at JAERI tandem to get double-differential cross section data of Fe, Ni and Cu in the energy region of 7 to 11 MeV. The D(d,n)^{3}He reaction was used as the neuron source. The gridded ionization chamber developed at Tohoku University was brought into JAERI tandem, and was irradiated with neutrons of 7.1, 7.9, 9.7 and 10.6 MeV. The details of the experimental procedure and some results were reported at the 1st RCM held at Debrecen.

After fiscal year of 1992, M. Baba's group has shifted their place of experiments from JAERI to Tohoku University because they have discovered that the $^{14}N(d,n)$ and $^{15}N(d,n)$ reactions available at Tohoku University are good sources of quasi-monoenergetic neutrons at 7.6 and 11.5 MeV, respectively. According to this change, we have also changed our effort to measurement of (n,α) cross sections by the activation method, although we have kept the research cooperation with them, and have financially supported the activities of M. Baba through a research contract. With regard to the activation data, we have tried to finalize the data measured in the energy region of 9 to 12 MeV with the $^{1}H(^{11}B,n)^{11}C$ neutron source at JAERI tandem (the first results have been presented at the Jülich conference). Efforts were put to obtain some new data, and also to characterize the energy spectra of source neutrons required for the correction of energy dependence of the cross sections inside the energy spread of peak neutrons. Details of the experiments with the $^{1}H(^{11}B,n)^{11}C$ neutron source and the results were presented at the 2nd RCM held at Beijing. We have also initiated a series of activation cross section measurement at 20 to 30 MeV region with the $^{7}Li(p,n)$ neutron source at JAERI tandem. This would be our recent contribution. Unfortunately, no definitive results on the (n,xα) reaction channels was obtained yet, although this activity is still on-going.

In the last a few years, the (n,α) cross sections of light mass nuclei were measured at the Fusion Neutronics Source (FNS). Measured were the (n,α) cross sections of ^{35}Cl, ^{17}O, ^{19}F, ^{23}Na, ^{37}Cl, ^{55}Mn and ^{89}Y and (n,nα) cross section of ^{18}O.

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SUMMARY OF RESULTS ACHIEVED UNDER RESEARCH AGREEMENT 6877/CF

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During this project the main attention was paid to improve the experimental technique to measure reaction cross sections and to supply additional information for the explanation of some unresolved issues for (n,α) reactions.

An α-spectrometer based on high-pressure Frisch-gridded ionization chamber was developed for complex studies of fast neutron induced α-particle emission reaction. The ^{58}Ni(n,α) reaction cross sections and α-particles angular distributions were measured at neutron energy range 3-6.5 MeV and at ~1 MeV.

The measurements were carried out in neutron beam of KG-2.5 and EG-1 accelerator of the IPPE. The D(d, n) reaction was used as neutron source. The thickness of the solid target was 0.65mg/cm^2. The Ni-target (0.25mg/cm^2) was placed at 30 cm distance from the neutron source. The neutron flux was measured against ^{238}U(n,f) reaction. The U-target was mounted on the back side of cathode in a back-to-back geometry. The experimental method and the measured data were delivered to RCM-2 [1] and were published in [2].

There are some unresolved problems in neutron induced α-emission reaction, i.e. reaction mechanism, α-emission in Coulomb sub-barrier region which are complicated for investigations through (n,α) reaction. The alternative way of the investigation with the (p,α)-reactions application was suggested to obtain some additional information [3].

According to RCM-2 recommendation, the measurements of the ^{54}Cr(p,α) reaction cross section were carried out at IPPE in proton energy range 6-8 MeV [4]. The α-particles were counted by thin ΔE-detector (Δt=50μm). The Cr-target (δt=10-80 μg/cm^2) and the α-detector were placed in the scattering camber with diameter 80 cm. The detector solid angle was 10^{-3} sr. The angle between proton beam and normal to the target was 15°. The target was exposed by 0.2-0.5 μA proton current. The data were normalized to the same charge of protons. The collected charge was 2-4 mC. These data indicate to the following facts:

- there are some evidence of the different reaction mechanism for α_0 and α_1 channels at low incident energies,

- angular distribution for (nucleon,α) reactions may change drastically (from symmetric to peaking forward) due to small energy shift of incident energy.

SUMMARY

The following work was performed at the IPPE in frame of CRP "Improvement of Measurements, Theoretical Computations and Evaluations of Neutron Induced Helium Production Cross Sections":

1. The α-spectrometer on the base of gridded ionization chamber was developed and used to measure the double-differential cross sections of (n,α)- reactions.

2. The angular distributions and the total cross sections of ^{58}Ni(n,α) reaction were measured at neutron energy range 3-6.5 MeV and at 1 MeV.

3. The importance of the reaction investigation in sub-Coulomb barrier region was highlighted. The investigation of (p,α) reaction was suggested to solve the problems which still exist.

4. The ^{54}Cr(p,α) reaction cross section and angular distributions were measured near 7 MeV proton energy. The angular distributions for α_0 and α_1 indicate the different mechanism of the reaction for these channels. However we need additional investigations to made final conclusion and to determine the contribution of the direct reaction mechanism.

5. Our results confirm that the share of direct reaction mechanism for (nucleon,α) reaction (at low energy as well) may be rather large. There is no systematics which can predict this contribution and might be used for data evaluation. Therefore we need new investigations of the (nucleon,α) reactions.

6. The IAEA Coordinated Research Program stimulated an interest to the problem. The IPPE plans to investigate the ^{17}O(n,α), Cr(n,α) reactions. The (p,α) experiment as well will be continued at nearest future.

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SUMMARY OF THE RESULTS ACHIEVED UNDER RESEARCH AGREEMENT 7128/CF

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Chief Scientific Investigator: Zelenetskij Andrei

During the time period of the CRP the following results have been obtained:

(1) A new investigation of a systematic behavior of (n,α) reaction cross sections at 14.5 MeV incident neutron energy has been carried out. The main object of the investigation was to obtain a more physically reliable systematic formula by taking into account the nonstatistical part of reaction and a new approach to create a cross section data base. The results were reported at the IAEA-RCM (Hungary, Debrecen, November 1992) [1] and a complete report was distributed among participants.

(2) The following work was to describe isomer yields in neutron reactions in the framework of modern theoretical models. A self-consistent description of $^{90m}Y(7+)$ isomer yields in (n,γ), (n,2n), (n,p) and (n,α) reactions have been obtained [2]. It has been shown that one can overcome the fundamental difficulty arising in calculating isometric cross sections - the lack of experimental γ-transition branching ratios for discrete levels - if one employ the ordinary statistical relations with correctly chosen energy dependence of the radiative strength functions. The proposed approach to calculate the isomeric level excitation functions in neutron induced reactions can be used successfully to determine the yields of long-lived isomers in fusion reactors. (Presented at the 1st RCM)

(3) New evaluations of (n,α) reaction cross sections for ADL-3 library have been carried out and the following work has been done:

- the file of level density parameters obtained in a frameworks of superfluid model has been updated;
- libraries of discrete levels and γ-transitions have been updated;
- the file of isomeric ratios has been updated;
- the impact of direct process contribution on (n,α) reaction cross section and emission spectra has been investigated in wide range of nuclide masses and energies of alpha-particles [3];
- the influence of possible difference between inverse reaction and absorption cross sections of alpha-particles on the (n,α) reaction cross sections and emission spectra has been investigated in a wide range of nuclide masses, neutron and alpha-particle energies [4].

The main results of the work have been reported during the second CRP meeting. In accordance with recommendations of the second CRP meeting, it was agreed to provide a theoretical interpretation of the $^{58}Ni(n,\alpha)$ reaction cross section behaviour below the Coulomb barrier using new experimental data of M. Baba, R. Haight and A. Goverdovskij near the reaction threshold. This work has been carried out in close cooperation with R. Capote Noy.

The careful theoretical investigations of $^{58}Ni(n,\alpha)$ reaction cross sections from reaction threshold to 20 MeV have shown that the calculation of the $^{58}Ni(n,\alpha)$ cross section by using currently available nuclear structure information (discrete level schemes, extracted level density parameters, parameters of optical model potentials, etc.) was a very difficult task. It is basically related to uncertainty in level density parameters because of the resonance data for main nuclides ^{58}Ni and ^{58}Co are absent. Besides, the uncertainty mentioned above in the level density parameters does not permit to draw a conclusion about the problem of so-called "inverse reaction cross section". The calculations show that agreement between the theoretical and experimental cross section data can be achieved in case of $^{58}Ni(n,\alpha)$ reaction without modification of alpha-particle potential parameters.

On the other hand, the calculations carried out of $^{56}Fe(n,\alpha)$ reaction cross sections clearly demonstrate the necessity to modify the parameters of alpha-particle potential to achieve agreement with new experimental data of R. Haight, M. Baba and E. Wattecamps. Moreover, preliminary results of new theoretical calculations of emission of alpha-particles have shown that Coulomb barrier for ingoing and outgoing alpha-particles can be essentially different.

The main results of the work been reported during the third RCM.

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SUMMARY OF WORK UNDER AGREEMENT 7051/CF

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The evaluated ^{58}Ni(n,α) cross sections in the EFF-2 (European), ENDF/B-VI (U.S.), and JENDL-3 (Japanese) libraries show large differences. The resolution of the differences between EFF-2 and ENDF/B-VI was the planned contribution for the first year of this Coordinated Research Program (CRP). It was found that most of these differences are due to factor-of-3 differences in the level densities used in the calculations performed for the evaluations. At the time these evaluations were being carried out, few data were available for this cross section, hence the heavy dependence on calculation. This part of the work has been reported in detail at the Debrecen RCM.

For the second year of the CRP, the level-density shape differences between Gilbert-Cameron (G-C) and Back-Shifted Fermi Gas (BSFG) were studied via calculated cross sections and particle emission spectra for ^{58}Ni for incident neutrons up to 20 MeV. Parameters for G-C were taken from the above work and those for BSFG were determined such that the resulting level densities agree with G-C at the top of the discrete-level region and near the neutron binding energy for ^{58}Ni, ^{58}Co, and ^{55}Fe. This procedure forces the level densities from the two formalisms to be as close as possible for the binary part of the calculation. The remaining differences are in the shapes of the two formalisms that, as shown at the Beijing RCM, are capable of causing the calculated cross sections and particle emission spectra to be different by up to 60%.

For the final year of this CRP, the Generalized Super-fluid Model (GSM) was added to the TNG code as a third level-density option. Again the shape effects were studied via ^{58}Ni. However, this time the calculations started with a new evaluation for the s-wave level spacing, D_0, for ^{55}Fe. The Fermi gas parameter **a** corresponding to this D_0 in the G-C formalism was determined using the G-C pairing correction and a standard formula for the spin cutoff parameter. The parameters for the constant temperature part of G-C were determined automatically in TNG. Since the D_0's for ^{58}Ni and ^{58}Co are not known experimentally, the corresponding **a**'s in the G-C formalism were found in a series of TNG calculations to fit approximately the (n,n'), (n,p) and (n,α) cross section data. Several new ^{58}Ni(n,α) data sets reported in the 1994 CRP meeting were taken into account in this fit. The parameters for BSFG and GSM were then obtained by forcing them to agree with G-C at two energies in the same manner as above to study the shape effects of the three formalisms. The use of a smaller D_0 for ^{55}Fe resulted in larger values for **a** for all three residual nuclides, which led to different (n,α) cross section shapes between G-C and BSFG than those reported at the Beijing RCM. The cross section ratios and particle-emission spectral ratios between GSM and G-C are markedly different from those between BSFG and G-C. This part of work is presented at the Sendai RCM.

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MEASUREMENTS OF HELIUM PRODUCTION REACTIONS WITH ACCELERATOR FACILITIES AT LOS ALAMOS

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O.A. Wasson (NIST), P. Maier-Komor (TU Munich), H. Vonach (IRK Vienna)
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Research Agreement 7909/CF
Chief Scientific Investigator: R.C. Haight

Our research on helium-production reactions under this CRP has employed two techniques: (1) measurement of helium accumulation following bombardment of samples with an intense monoenergetic neutron source of E_n=10 MeV and (2) measurement of alpha-particle production cross sections, angular distributions and emission spectra as functions of neutron energy from threshold to 50 MeV with a spallation neutron source.

Data from the helium accumulation method have been reported and recently submitted for publication for the following materials: ^{56}Fe, ^{58,60,61}Ni, ^{nat}Fe, ^{nat}Ni and ^{nat}Cu. Uncertainties in the cross sections range from 5 to 20%.

The spallation neutron source (LAMPF/WNR/LANSCE) is used for measurements of (n,xα) reactions over the continuous energy range from threshold to 50 MeV. Double differential cross sections (DDX) allow detailed comparisons with nuclear reaction model predictions and provide data directly on alpha-particle production cross sections, on partial KERMA factors (Kinetic Energy Released in Materials), and on partial heavy-ion recoil distributions.The following materials are being studied. C, O, N, ^{27}Al, Si, ^{51}V, ^{56}Fe, ^{59}Co, ^{58,60}Ni, ^{89}Y and ^{93}Nb. Of these, the ^{59}Co(n,xα) was chosen for detailed comparison with published ^{59}Co(n,xHe) and (n,xα) data, available only near 14 MeV, and with activation data at lower neutrons energies where the only alpha-particle-producing channel is ^{59}Co(n,α)^{56}Mn. This study shows that our results are very consistent with literature data where comparisons can be made. In addition, the data can be understood in terms of statistical and pre-equilibrium reaction models providing the correct input parameters are chosen. Preliminary results for ^{58}Ni and ^{60}Ni have been obtained and agree well with preliminary results from other members of this CRP.

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CONTRIBUTION FROM INSTITUTE FOR REFERENCE MATERIALS AND MEASUREMENTS, GEEL, BELGIUM
Provided by E. WATTECAMPS

"Measured and calculated differential and total yield cross section data of $^{58}Ni(n,x\alpha)$ and $^{63}Cu(n,xp)$ in the neutron energy range from 2.0 to 15.6 MeV"

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Double differential (n,xp) and (n,xα) cross section ratio measurements are performed at the 7 MV Van de Graaff accelerator laboratory for neutron energies between 2.0 and 15.6 MeV. The following reaction rate ratios are measured: $^{58}Ni(n,x\alpha)$ to $^{27}Al(n,\alpha)$, $^{58}Ni(n,x\alpha)$ to $^{58}Ni(n,p)$, $^{63}Cu(n,xp)$ to $^{27}Al(n,\alpha)$ and $^{63}Cu(n,xp)$ to $^{58}Ni(n,p)$. Protons or alphas are detected by ΔE-ΔE telescopes under 14, 51, 79, 109 and 141 degree. The energy spectrum of the emitted particles and the angular yield distribution are measured. First the measurements provide double differential cross section data for $^{27}Al(n,\alpha)$ and $^{58}Ni(n,p)$ by normalization to the known total yield reference cross section values. Subsequently, the reaction rate ratios of $^{58}Ni(n,x\alpha)$ and $^{63}Cu(n,xp)$ to $^{27}Al(n,\alpha)$ or $^{58}Ni(n,p)$ provide double differential cross sections of $^{58}Ni(n,x\alpha)$ and $^{63}Cu(n,xp)$ in barn/MeV.sr. The measured double differential cross section data, the particle energy spectra, the angular distributions and the total yield cross section data are compared with measured data from literature and with nuclear reaction model calculations performed at IRMM with the computer codes STAPRE-H and EXIFON.

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ACTIVATION CROSS SECTION MEASUREMENTS AT TOHOKU UNIVERSITY

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Introduction

This report is prepared to introduce nuclear data activities of the author's group, especially for activation cross section measurements in the Dynamitron laboratory at Tohoku University. The report includes four topics, i.e., activation cross section measurements between 12 and 20 MeV using T+d neutron source; activation cross section measurements using other sources; integral test of dosimetry reactions, and the evaluations of dosimetry cross sections.

I. Activation cross section measurements from 12 to 20 MeV

Reliable excitation functions between 12-20 MeV have been measured using the T(d,n)4He reaction. The reaction $^{93}Nb(n,2n)^{92m}Nb$ was adopted as the reference one in this energy range[1]; the data base of this reaction (IAEA standard file) was also validated by the ratio measurement to the standard $^{27}Al(n,\alpha)^{24}Na$ cross section [1].

Total 23 reactions have been measured for 15 elements [2,3,4]. Most of the reported cross sections were for (n,2n) reactions with high threshold energies because the effect of the contaminated neutrons due to the $D(d,n)^{3}He$ should be very carefully corrected in the case of the lower threshold energy reactions.

The results are summarized as follows:

- all cross section data have been compared with JENDL-3 or other special purpose files, such as for dosimetry, and activations. Most of the results have confirmed the evaluations.

- some of the cross sections have been used for the update of JENDL DOSIMETRY FIlE (JDF) [5,6].

- a new reaction, $^{58}Ni(n,p\alpha)^{54}Mn$ have been discovered in the present study. The cross section of this reaction was almost double of the theoretical model calculation by SINCROS-II with the default model parameter set.

II. Activation cross section measurement with other neutron sources

Cross section of $^{93}Nb(n,n')^{93m}Nb$, one of the most important reactor dosimetry reaction was measured using the $D(d,n)^{3}He$ neutron source. The results were consistent with the previous data measured below 6 MeV.

The reaction $^{63}Cu(n,p)^{63}Ni$ leading to long-lived, low-energy beta emitter is important for the radiation control in the large accelerator facilities and also good tracer in the fast neutron dose estimate in Hiroshima and Nagasaki. The cross section measurement was proposed by Y. Uwamino et al. (RIKEN), and experiments were carried out using three neutron sources, T(p,n), D(d,n) and T(d,n) reactions. Tentative results were discrepant to those of JENDL-3.

III. Integral test of activation cross sections

Integral test was carried out for the 13 important dosimetry cross sections using the broad energy neutron field provided by thick target Li(d,n) reaction [7,8]. These data have used for the integral test of JDF and other dosimetry files together with other various neutron fields. In particular, the test in the Li(d,n) field revealed the inadequacy of the ENDF/B-VI data for $^{23}Na(n,2n)$, while other field tests could not indicate due to the low sensitivity to this reaction.

IV. Evaluation of dosimetry cross sections

Update of JDF is ongoing. Five cross sections have been evaluated by the Cubic B-spline fitting method by the present author, providing covariance data simultaneously [9]. In this evaluation, the newly evaluated data for the above mentioned reaction $^{23}Na(n,2n)$ are consistent with the integral test.

For the high energy dosimeter, evaluation based on theoretical model calculation has been made for cobalt up to 50 MeV [10,11]. The calculated results reproduced a small number of available experimental data above 20 MeV, especially for $^{59}Co(n,2n\alpha)^{54}Mn$ [12]; this reaction can be a new dosimetry reaction in the energy range between 30-50 MeV. The theoretical curve of the total helium production cross section above 30 MeV, however, could not reproduce the trend of the data measured by Goeckner, et al. [13], and revised data reported by Haight at this meeting [14]; this means that further adjustment of the model parameters should be necessary .

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HELIUM ATOMS MEASUREMENT SYSTEM AND HELIUM PRODUCTION CROSS SECTION MEASUREMENT

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A system named the Helium Atoms Measurement System (HAMS) has been developed for the purpose of measuring helium production cross sections. The HAMS is composed of three blocks: a gas releaser, a mass spectrometer, a standard He supply, which are evacuated by turbo-molecular pumps to an ultra high vacuum. A solid sample containing helium is evaporated with the gas releaser. The released gases are purified with a trap of a Ti-getter pump and then are introduced into the mass spectrometer. The mass spectrometer has a quadrupole mass spectrometer (QMS), a digital electrometer, and a personal computer. A signal measured by the QMS is converted to digital data by using the digital electrometer and the digital data are stored in the personal computer with additional information about conditions of the measurement. Calibration of the HAMS is carried out with standard He gases produced by the standard He supply. The total uncertainty of the apparatus is 4.4 % in the measurement of 1×10^{10} He atoms.

Helium production cross sections for Al and Si have been measured by using the HAMS. Al and Si samples were irradiated with an intense d-T neutron source of Japan Atomic Energy Research Institute. The samples are set around the d-T neutron source. Neutron energies at those sample positions vary from 14.2 MeV to 14.9 MeV according to the neutron emission angles. The He production cross sections measured by HAMS agree with early experimental data within the error.

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"(n,xα) REACTION CROSS SECTIONS UP TO 50 MeV"

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SUMMARY OF CONTRIBUTION TO THE IAEA CRP

Based on the successful study of cross section calculations from above the resonance region to 20 MeV, the extension of incident energy region up to 50 MeV has been tried. In this research, the calculations of (n,xα) reaction cross sections for Cr, Fe, and Ni are presented. Two important improvements of the EGNASH-3 program are performed. One is the excitation energy dependence of the level density parameter "a" related with the shell correction energy. Second, the real and imaginary diffuseness parameters in the optical potential for α-particle is increase by 5 to 25%, depending on the target nuclei, to fit the experimental data.

The (n,xα) reaction cross sections for targets ^{50}Cr and ^{52}Cr are calculated and compared with experimental data. They show almost good agreement.

Calculated ^{56}Fe(n,xα) reaction cross sections are compared with experimental data and show good agreement from threshold to 14 MeV. Natural Fe(n,α) cross section show really same energy dependent and about 5% larger than ^{56}Fe(n,α) reaction around 14 Mev. Overall agreement between calculated helium production cross sections and the experimental data can be shown.

The comparison between the calculation and experimental data of ^{58}Ni(n,α) cross sections shows good agreement from 5 MeV to 15 MeV. In the case of ^{60}Ni, the calculation is middle value of two data of experiments at 10 MeV and the lower at 15 MeV. Making up curves from ^{58}Ni and ^{60}Ni calculations and many experimental data of natural Ni(n,xα) reaction cross sections are compared. Below 10 MeV, there are two groups of experimental values, and smaller experimental data agree with the calculated one.

Nuclear reaction (n,2n2p) produces the same nucleus as nuclear reaction (n,α), but does not emit helium particle. In the ^{58}Ni+n reaction, there is larger helium production than in (n,α)+(n,2n2p) reaction from 25 MeV to 35 MeV, because (n,2α) reaction occurs, but in ^{60}Ni+n reaction there is almost no observation of this situation. Above 35 MeV, (n,2n2p) reaction is generated over (n,α) reaction, so that the difference between (n,xα) + (n,x2n2p) cross sections and helium-production cross sections becomes larger.

As an example of proton induced helium production reaction, Ni(p,αxn)^{55}Co production cross section is calculated and compared with the experimental data, which agree with the calculation except near threshold and about 30 MeV. The calculations for (n,xα) reaction cross sections show the usefulness of EGNASH 3 code.

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