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INVESTIGATION OF THE GENERATION OF SEVERAL LONG-LIVED RADIONUCLIDES OF IMPORTANCE IN FUSION REACTOR TECHNOLOGY: REPORT ON A COORDINATED RESEARCH PROGRAM SPONSORED BY THE INTERNATIONAL ATOMIC ENERGY AGENCY

Donald L. Smith
Technology Development Division
Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60439, U.S.A.

Anatoly B. Pashchenko
Nuclear Data Section
International Atomic
Energy Agency, Box 100
A-1400 Vienna, Austria

ABSTRACT

The IAEA initiated a Coordinated Research Program (CRP) in 1988 to obtain reliable information for 16 long-lived activation reactions of special importance to fusion reactor technology: ^{27}Al(n,2n)^{26}Al, ^{63}Cu(n,p)^{63}Ni, ^{94}Mo(n,p)^{94}Nb, ^{109}Ag(n,2n)^{108m}Ag, ^{179}Hf(n,2n)^{178m2}Hf, ^{182}W(n,n'α)^{178m2}Hf, ^{151}Eu(n,2n)^{150g}Eu, ^{153}Eu(n,2n)$^{152g+m2}$Eu, ^{159}Tb(n,2n)^{158}Tb, ^{158}Dy(n,p)^{158}Tb, ^{193}Ir(n,2n)^{192m2}Ir, ^{187}Re(n,2n)^{186m}Re, ^{62}Ni(n,γ)^{63}Ni, ^{98}Mo(n,γ)^{99}Mo(β-)^{99}Tc, ^{165}Ho(n,γ)^{166m}Ho and ^{191}Ir(n,γ)^{192m2}Ir. This paper documents progress achieved from the start of the program through mid-1993.

I. INTRODUCTION

A list of 16 important activation cross sections for fusion materials was presented by E. Cheng at the 1986 Gaussig Advisory Meeting on Nuclear Data for Fusion Reactor Technology. This list was subsequently endorsed by Working Group I at this meeting.[1] The issue was also put forth by Cheng at the 1987 INDC Meeting.[2] On the strength of this input, the IAEA formed a Coordinated Research Program (CRP) in 1988 entitled "Activation Cross Sections for the Generation of Long-lived Radionuclides of Importance in Fusion Reactor Technology". There are presently 10 research agreement holders affiliated with this CRP, and 57 individuals have contributed directly to the work of the program (see Table 1).[5] Many others have been involved in research efforts indirectly related to this CRP.

The work of this CRP has been documented in the proceedings of three coordination meetings[3-5], and its status through mid-1991 was reported at the Juelich Conference.[6] The investigations fall into three categories: i) cross section measurements (most are near 14 MeV but some results have been reported at other energies, especially for neutron capture), ii) evaluations (including those based on systematics), and iii) nuclear model calculations intended to define excitation functions for the reactions considered. Results from this program are summarized below.

Table 1: Contributors to the IAEA CRP on activation cross sections for long-lived radionuclides

Austria

Institut fuer Radiumforschung und Kernphysik-Vienna (IRK)
H. Vonach[a], M. Wagner

International Atomic Energy Agency-Nuclear Data Section (IAEA)
A. Pashchenko[b]

China (Peoples' Republic)

Institute of Atomic Energy-Beijing (IAE)
Lu Hanlin[a], Yu Weixiang, Zhao Wenrong, Zhao Yiwu

Lanzhou University (LU)
Wang Yongchang, Yuan Junqian, Wang Huamin, Ren Zhongling, Yang Jingkang

Peking University (PU)
Shi Zhoaming

Sichuan University (SU)
Xia Yijun, Wang Chunhao, Long Xianguan, Yang Jingfu, He Fuging, Yang Zhihua, Peng Xiufeng, Liu Mantian, Luo Xiaobing

Germany
Forchungszentrum-Geesthact (FZG)
H. Agrawal, R. Pepelnik
Forchungszentrum-Juelich (FZJ)
S. Qaim[a]

Hungary
Institute of Experimental Physics-Debrecen (IEP)
Cs. M. Buczko, F. Cserpak, J. Csikai[a]

Italy
Centro di Calcolo - Bologna (ENEA)
G. Maino[a]

Japan
Data Engineering, Inc. (DE)
N. Yamamuro
Japan Atomic Energy Research Institute-Tokai (JAERI)
Y. Ikeda, C. Konno

Russia
Institute of Physics and Power Engineering-Obninsk (IPPE)
O. Grudzevich, A. Ignatyuk[a], N. Kornilov, A. Pashchenko[b], A. Zelenetsky, K. Zolotarev
V.G. Khlopin Radium Institute-St. Petersburg (KRI)
M. Blinov[a] (died in 1993), S. Chuvaev, A. Filatenkov[a] (alternate for Blinov), B. Gavrilov, B. Shirvaev

United Kingdom
Harwell Laboratory and Euratom Fusion Association (HL-EFA)
R. Forrest[a], B. Patrick, L. Russen, M. Sowerby, C. Wilkins

United States
Argonne National Laboratory (ANL)
L. Greenwood, J. Meadows, D. Smith[a]
Lawrence Livermore National Laboratory (LLNL)
M. Chadwick[ab], D. Gardner, M. Gardner
Los Alamos National Laboratory (LANL)
M. Chadwick[ab], R. Haight, P. Young
Oak Ridge National Laboratory (ORNL)
C. Fu
TSI Research-Solana Beach (TSI)
E. Cheng

[a] IAEA CRP research agreement holder.[5]
[b] Affiliated with more than one organization during CRP.

II. MEASUREMENTS AND EVALUATIONS

The original request from the fusion community was for activation cross section data in the vicinity of 14 MeV for particle-emission reactions, and below a few MeV for (n,γ) reactions. Most of the measurement effort has been carried out near 14 MeV because intense neutron sources were needed to produce adequate yield of the long-lived activities of interest to the CRP. These could be obtained from neutron generators at several laboratories. However, some data were also obtained for particle-emission reactions at lower energies, including integral data in the Be(d,n) neutron field. It is recognized that such information will be useful in testing the results from nuclear model calculations that were also carried in the CRP.

For some cases where needed information was very difficult to obtain directly from experiments, it has been possible to estimate the cross sections by subtracting experimental values for short-lived components from total reaction cross sections $\approx$ 14 MeV that were derived from systematic considerations.

The compiled 14-MeV data for 7 particle-emission reactions were evaluated in order to provide suggested values to be used in applications by the fusion energy community. They also served to normalize the results of certain nuclear model calculations carried out by the CRP.

III. NUCLEAR MODEL CALCULATIONS

A nuclear modeling effort for several reactions has been carried out in parallel with the experimental program. For 8 of these, more than one investigator calculated the cross sections from threshold to 14 MeV. These results were then normalized to evaluated 14-MeV cross sections, thus providing evaluated excitation functions (see Figures 1-8).

IV. CONCLUSIONS

This CRP has produced extensive results relevant to the reactions on the original list, thereby greatly improving the nuclear data base for fusion energy applications. The status is now reasonably acceptable for 12 of the reactions considered. However, there are unacceptable uncertainties for the 6 remaining reactions. Poor knowledge of the decay half life remains a concern for several of these reactions. The status of each reaction is given in the Appendix. In addition, this CRP has spawned studies in related areas not discussed in this paper. These have also contributed significantly to improving our general knowledge of neutron-induced activation processes. Consequently, this CRP has clearly been one of the most successful undertakings of its kind.

ACKNOWLEDGEMENTS

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FIGURES

Nuclear model results for 8 reactions examined by the CRP are compared after normalizing to a common value at 14.5 MeV. Evaluated excitation functions are obtained by averaging on a common energy grid and using spline fitting.

^{94}Mo(n,p)$^{94g+m}$Nb [6+,2x10^4 yr + 3+, 6.26 min]

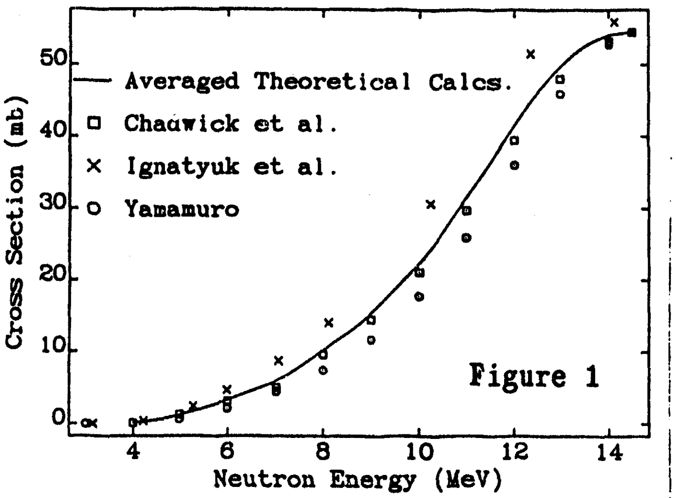


Figure 1

^{109}Ag(n,2n)^{108m}Ag [6+, 433 yr]

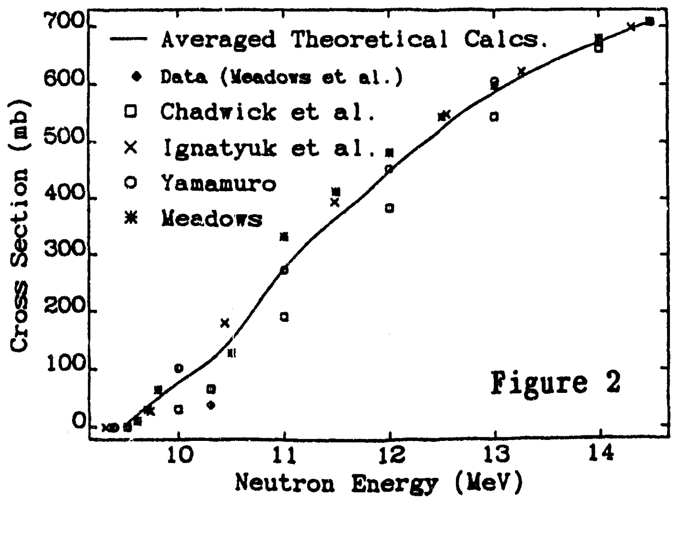
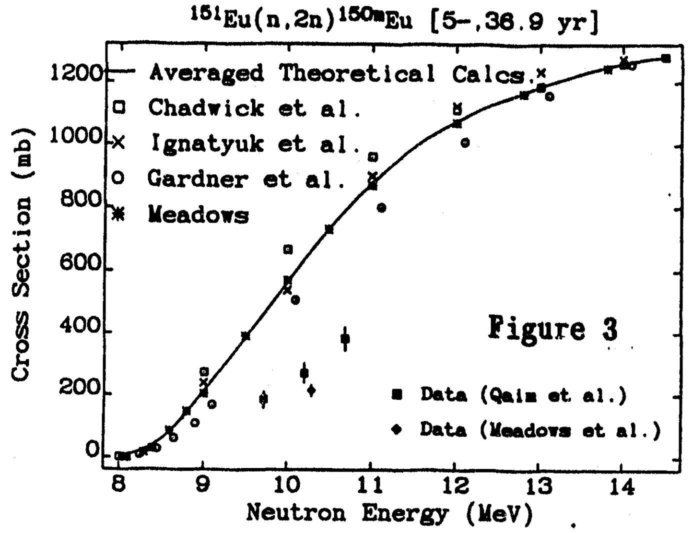
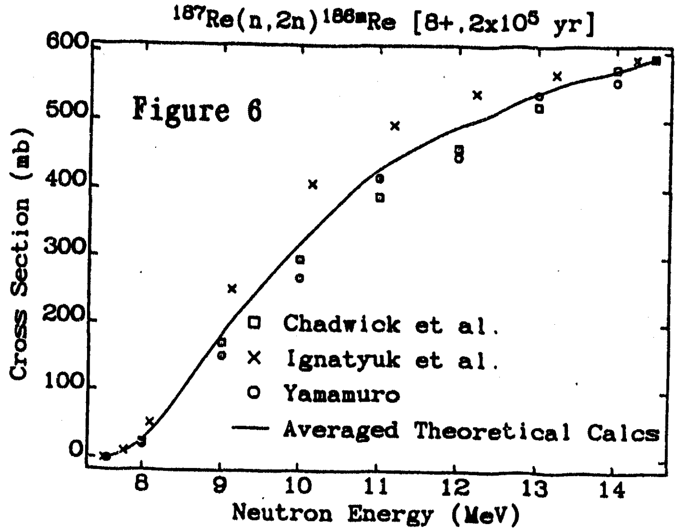
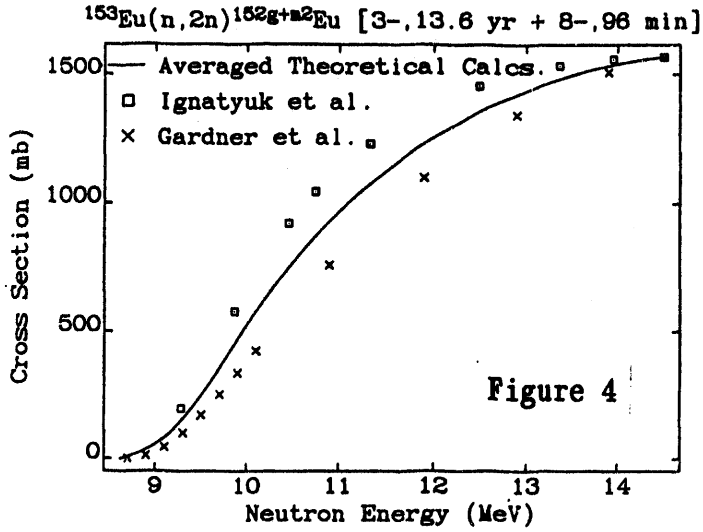
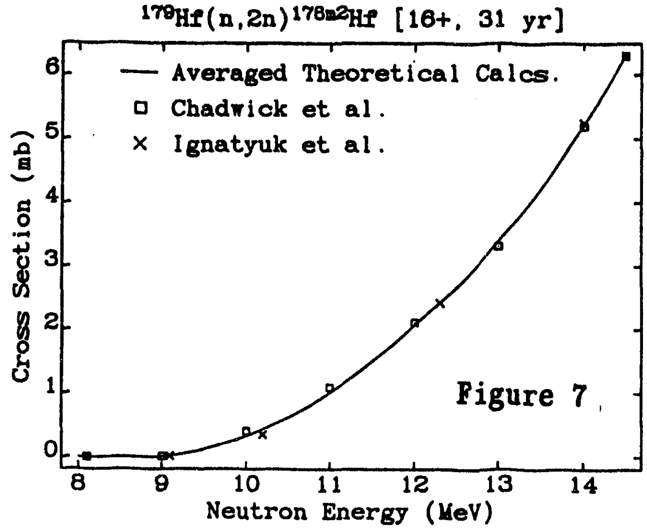


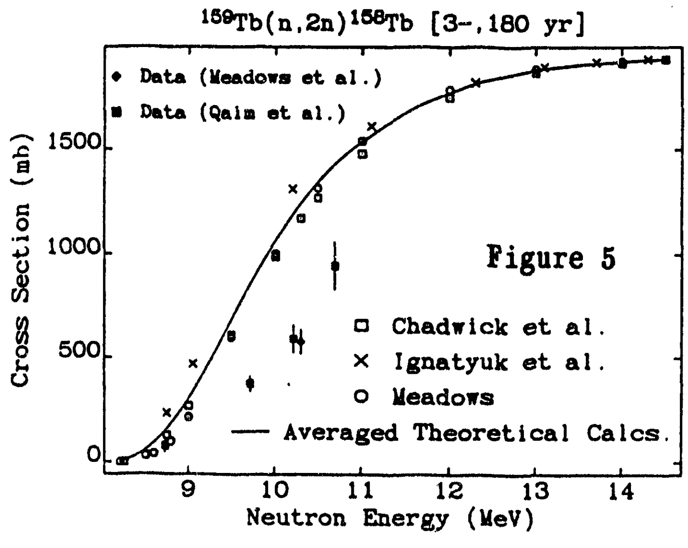
Figure 2

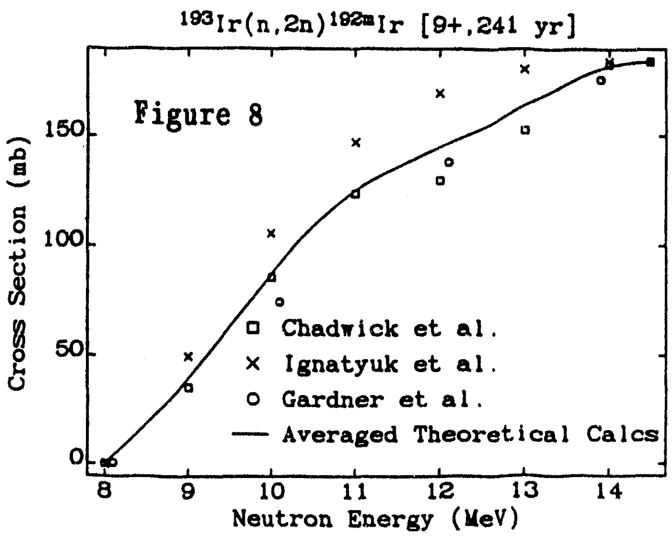

151Eu(n,2n)150mEu [5-,36.9 yr]
Averaged Theoretical Calcs.
Chadwick et al.
Ignatyuk et al.
Gardner et al.
Meadows
Data (Qaim et al.)
Data (Meadows et al.)
Figure 3
Cross Section (mb)
Neutron Energy (MeV)


187Re(n,2n)186mRe [8+,2x10^5 yr]
Figure 6
Chadwick et al.
Ignatyuk et al.
Yamamuro
Averaged Theoretical Calcs
Cross Section (mb)
Neutron Energy (MeV)


153Eu(n,2n)152g+m2Eu [3-,13.6 yr + 8-,96 min]
Averaged Theoretical Calcs.
Ignatyuk et al.
Gardner et al.
Figure 4
Cross Section (mb)
Neutron Energy (MeV)


179Hf(n,2n)178m2Hf [16+, 31 yr]
Averaged Theoretical Calcs.
Chadwick et al.
Ignatyuk et al.
Figure 7
Cross Section (mb)
Neutron Energy (MeV)


159Tb(n,2n)158Tb [3-,180 yr]
Data (Meadows et al.)
Data (Qaim et al.)
Figure 5
Chadwick et al.
Ignatyuk et al.
Meadows
Averaged Theoretical Calcs.
Cross Section (mb)
Neutron Energy (MeV)


193Ir(n,2n)192mIr [9+,241 yr]
Figure 8
Chadwick et al.
Ignatyuk et al.
Gardner et al.
Averaged Theoretical Calcs
Cross Section (mb)
Neutron Energy (MeV)

APPENDIX: Status of CRP Reactions

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

Properties: Half life = 7.2 x 10^5 years. Threshold = 13.55 MeV. Decay = ϵ (100%). Dominant γ-ray = 1809 keV (99.8%).
Data Available Prior to CRP: Some cross section values for both long-lived ground state (g) and short-lived isomer (m).[7] Can estimate long-lived (g) component from $\sigma_g(n,2n) = \sigma_{tot}(n,2n) - \sigma_m(n,2n)$. Derive $\sigma_{tot}(n,2n)$ from systematics. Large uncertainty due to neutron energy dependence and determination of $\sigma_{tot}(n,2n)$ from systematics.
Sample Irradiations in CRP: IEP (14.6 MeV).
Experimental Cross Sections from CRP: None.
Nuclear Model Cross Sections from CRP: DE, IEP, IPPE.
Evaluations from CRP: None.
Status: Several model calculations but no new data from CRP. Uncertainty remains significant.

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

Properties: Half life = 100.1 years. Threshold = None (exoergic reaction). Decay = β- (100%). No γ-rays.
Data Available Prior to CRP: Some cross section values around 14 MeV.[7] Significant discrepancies observed.
Sample Irradiations in CRP: FZJ/IEP (5.4-12.3, 14.5 MeV), ANL/JAERI/LANL (10.3, 14.7 MeV and continuum neutrons from 7 MeV deuterons on thick Be target), HL-EPA (14.8 MeV).
Experimental Cross Sections from CRP: None. Results pending from FZJ/IEP effort. Samples irradiated in ANL/JAERI/LANL effort not analyzed due to end of ANL program.
Nuclear Model Cross Sections from CRP: ORNL, DE, IAE, IEP.
Evaluations from CRP: None.
Status: Results of several model calculations from CRP need to be compared with each other and with existing data. Experimental results from the FZJ/IEP effort (if successful) will be useful in defining the excitation function since the shapes obtained from nuclear modeling studies vary considerably. Knowledge of the 14-MeV cross section alone is inadequate for such a low threshold reaction. Uncertainty remains significant.

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

Properties: Half life = 2.03 x 10^4 years. Threshold = 1.28 MeV. Decay = β- (100%). Dominant γ-ray = 871 keV (99.9%).
Data Available Prior to CRP: Some cross section values for both long-lived ground state (g) and short-lived isomer (m).[7] What counts for fusion applications is $\sigma_{tot}(n,p)$ since isomeric level decays within a few seconds to ground state. Can estimate $\sigma_{tot}(n,p)$ from systematics but this involves a large uncertainty. CRP experimental efforts directed toward direct measurement of this cross section.
Sample Irradiations in CRP: JAERI (14.1-14.8 MeV), IEP (14.6 MeV), IRK ($\approx$ 14 MeV).
Experimental Cross Sections from CRP: JAERI (14.1-14.8 MeV).
Nuclear Model Cross Sections from CRP: IAE, LANL/LLNL, IPPE, DE, IEP.
Evaluations from CRP: Experimental data $\approx$ 14 MeV evaluated at IRK. Nuclear model results evaluated at LLNL.
Status: Experimental results $\approx$ 14 MeV have been evaluated at IRK. Data are reasonably consistent. Results from nuclear modeling at several laboratories (normalized at 14.5 MeV) have been averaged to produce a recommended excitation function for $\sigma_{tot}(n,p)$. Differences in shapes from individual calculations are modest. Due to CRP efforts, cross section probably is known adequately for fusion energy applications.

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

Properties: Half life = 418 years. Threshold = 9.39 MeV. Decay = ϵ (91.3%), IT (8.7%). Dominant γ-ray = 723 keV (90.8%).
Data Available Prior to CRP: Some cross section values for both long-lived isomeric state (m) and short-lived ground state (g).[7] Can estimate long-lived (m) component from $\sigma_m(n,2n) = \sigma_{tot}(n,2n) - \sigma_g(n,2n)$. Derive $\sigma_{tot}(n,2n)$ from systematics. Large uncertainty due to neutron energy dependence and derivation of $\sigma_{tot}(n,2n)$ from systematics. Discrepancy existing between experimental values and result from systematics traced to a serious error in half life.
Sample Irradiations in CRP: IAE (14.2-14.8 MeV), IEP/FZG (14.5 MeV), KRI (13.7-14.9 MeV), ANL/JAERI/LANL (10.3, 14.7 MeV and continuum neutrons from 7 MeV deuterons on thick Be target), LU (13.6-14.8 MeV).
Experimental Cross Sections from CRP: IAE (14.2-14.8 MeV), IEP/FZG (14.5 MeV), KRI (13.7-14.9 MeV), ANL/JAERI/LANL (10.3, 14.7 MeV), LU (13.6-14.8 MeV).
Nuclear Model Cross Sections from CRP: IAE, DE, IPPE, ANL, LANL/LLNL.
Evaluations from CRP: Experimental data $\approx$ 14 MeV evaluated at IRK. Nuclear model results evaluated at LLNL.
Status: Experimental results $\approx$ 14 MeV have been evaluated at IRK. Data are reasonably consistent. Results from nuclear modeling at several laboratories (normalized at 14.5 MeV) have been averaged to produce a recommended excitation function for $\sigma_{tot}(n,p)$. Differences in shapes from individual calculations are modest. Due to CRP efforts, cross section probably is known adequately for fusion energy applications.

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

Properties: Half life = 31 years. Threshold = 8.58 MeV. Decay = IT (100%). Dominant γ-ray = 426 keV (97.1%).
Data Available Prior to CRP: No data found for long-lived isomer (m2), some data reported for short-lived isomer (m1).[7] There is no way to estimate $\sigma_{m2}(n,2n)$ from systematics without knowing isomer ratios.
Sample Irradiations in CRP: HL/EPA (14.8 MeV), IAE/LU (14.2-14.8 MeV), ANL/JAERI/LANL (10.3, 14.7 MeV and continuum neutrons from 7 MeV deuterons on thick Be target).
Experimental Cross Sections from CRP: HL/EPA (14.8 MeV), IAE/LU (14.2-14.8 MeV), JAERI/ANL (14.7 MeV).
Nuclear Model Cross Sections from CRP: LANL/LLNL, IPPE
Evaluations from CRP: Experimental data $\approx$ 14 MeV evaluated at IRK. Nuclear model results evaluated at LLNL.
Status: Experimental results $\approx$ 14 MeV have been evaluated at IRK. Data are reasonably consistent. Results from nuclear modeling at two laboratories (normalized at 14.5 MeV) have been averaged to produce a recommended excitation function for $\sigma_{m2}(n,2n)$. Differences in shapes from individual calculations are modest. Due to CRP effort, cross section appears to be known well enough for fusion energy applications.

^{182}W(n,n'α)^{178m2}Hf

Properties: Half life = 31 years. Threshold = 8.58 MeV. Decay = IT (100%). Dominant γ-ray = 426 keV (97.1%).
Data Available Prior to CRP: None.[7]
Sample Irradiations in CRP: HL/EPA (14.8 MeV), JAERI (14.8 MeV), HL/EPA (14.8 MeV), KRI(14.9 MeV), IAE/LU (14.2 MeV).
Experimental Cross Sections from CRP: JAERI (14.8 MeV), KRI (14.9 MeV), IAE/LU (14.2 MeV).
Nuclear Model Cross Sections from CRP: None.
Evaluations from CRP: Experimental results $\approx$ 14 MeV have been evaluated at IRK.
Status: The CRP effort provides a qualitative knowledge of the cross section $\approx$ 14 MeV. Uncertainty remains significant.

^{151}Eu(n,2n)^{150g}Eu

Properties: Half life = 35.8 years. Threshold = 8.02 MeV. Decay = ϵ (100%). Dominant γ-ray = 334 keV (94.0%). There exists some confusion as to whether the long-lived state is the ground state (g) or the isomer (m). Current best knowledge indicates that it is the ground state.
Data Available Prior to CRP: Several cross section values for both long-lived ground state and short-lived isomer.[7] Can estimate long-lived (g) component from $\sigma_g(n,2n) = \sigma_{tot}(n,2n) - \sigma_m(n,2n)$. Derive $\sigma_{tot}(n,2n)$ from systematics. Large uncertainty due to neutron energy dependence and $\sigma_{tot}(n,2n)$ determined from systematics.
Sample Irradiations in CRP: IAE/LU (14.2-14.8 MeV), FZJ/IEP (8.7-10.7 MeV)[8], KRI (13.5-14.9 MeV), JAERI (14.1-14.8 MeV), ANL/JAERI/LANL (10.3, 14.7 MeV and continuum neutrons from 7 MeV deuterons on thick Be target).
Experimental Cross Sections from CRP: IAE/LU (14.2-14.8 MeV), KRI (13.5-14.9 MeV), FZJ/IEP (8.7-10.7 MeV)[8], JAERI (14.1-14.8 MeV), ANL/JAERI/LANL (10.3, 14.7 MeV and continuum neutrons from 7 MeV deuterons on thick Be target).
Nuclear Model Cross Sections from CRP: LANL/LLNL, IPPE, ANL.
Evaluations from CRP: Experimental data $\approx$ 14 MeV evaluated at IRK. Nuclear model results evaluated at LLNL.

Status: Experimental results ≈ 14 MeV have been evaluated at IRK. Data are reasonably consistent. Results from nuclear modeling at two laboratories (normalized at 14.5 MeV) have been averaged to produce a recommended excitation function for σ_g(n,2n). Differences in shapes from individual calculations are modest. Due to CRP efforts and previously existing data, the cross section appears to be known adequately for fusion energy applications

^{153}Eu(n,2n)$^{152g+m2}$Eu
Properties: Half life = 13.54 years. Threshold = 8.61 MeV. Decay = ϵ (72.1%), β-(27.9%). Dominant γ-ray = 344 keV (26.6%). There are two shorter-lived isomers (m1 and m2) as well as the long-lived ground state (g) of ^{152}Eu involved in this reaction. Their relative contributions can be sorted out only by performing activity measurements at various times following irradiation. m2 decays only to g, and m1 decays to neighboring elements. Activity measurements made long after the irradiation yield g+m2, and m1 is bypassed.
Data Available Prior to CRP: Several cross section values for both long-lived ground state and short-lived isomers.[7] Can estimate long-lived (g+m2) component from σ_{g+m2}(n,2n) = σ_{tot}(n,2n) - σ_{m1}(n,2n). Derive σ_{tot}(n,2n) from systematics. Large uncertainty due to neutron energy dependence and σ_{tot}(n,2n) derived from systematics.
Sample Irradiations in CRP: IAE/LU (14.8 MeV), KRI (13.5-14.9 MeV), ANL/JAERI/LANL (10.3, 14.7 MeV and continuum neutrons from 7 MeV deuterons on thick Be target), JAERI (14.1-14.8 MeV).
Experimental Cross Sections from CRP: IAE/LU (14.8 MeV), KRI (13.5-14.9 MeV), ANL/JAERI (14.7 MeV), JAERI (14.1-14.8 MeV).
Nuclear Model Cross Sections from CRP: LLNL, IPPE, IAE.
Evaluations from CRP: Experimental data ≈ 14 MeV evaluated at IRK. Nuclear model results evaluated at LLNL.
Status: Experimental results ≈ 14 MeV have been evaluated at IRK. Data are reasonably consistent. Results from nuclear modeling at two laboratories (normalized at 14.5 MeV) have been averaged to produce a recommended excitation function for σ_{g+m2}(n,2n). Differences in shapes from individual calculations are modest. Due to CRP efforts and previously existing data, the cross section appears to be known adequately for fusion energy applications.

^{159}Tb(n,2n)^{158}Tb
Properties: Half life = 150 years. Threshold = 8.18 MeV. Decay = ϵ (82%), β-(18%). Dominant γ-ray = 944 keV (43%).
Data Available Prior to CRP: Several cross section values for both long-lived ground state (g) and short-lived isomer (m).[7] Only counts immediately after irradiation can separate isomeric component. Most counts yield σ_{tot}(n,2n) = σ_g(n,2n) + σ_m(n,2n). Can also derive σ_{tot}(n,2n) from systematics, but with substantial uncertainty.
Sample Irradiations in CRP: PZJ/IEP (8.7-10.7 MeV)[8], ANL/JAERI/LANL (10.3, 14.7 MeV and continuum neutrons from 7 MeV deuterons on thick Be target), IAE/LU (14.2-14.8 MeV).
Experimental Cross Sections from CRP: IAE/LU (14.2-14.8 MeV), PZJ/IEP (8.7-10.7 MeV)[8], ANL/JAERI/LANL (10.3, 14.7 MeV and continuum neutrons from 7 MeV deuterons on thick Be target).
Nuclear Model Cross Sections from CRP: LANL/LLNL, IPPE, ANL, IAE, DE.
Evaluations from CRP: Experimental data ≈ 14 MeV evaluated at IRK. Nuclear model results evaluated at LLNL.
Status: Experimental results ≈ 14 MeV have been evaluated at IRK. Data are reasonably consistent. Results from nuclear modeling at several laboratories (normalized at 14.5 MeV) have been averaged to produce a recommended excitation function for σ_{tot}(n,2n) = σ_{g+m}(n,2n). Differences in shapes from individual calculations are modest. Due to CRP efforts and previously existing data, the cross section appears to be known adequately for fusion energy applications.

^{158}Dy(n,p)^{158}Tb
Properties: Half life = 150 years. Threshold = None (exoergic reaction). Decay = ϵ (82%), β-(18%). Dominant γ-ray = 944 keV (43%).
Data Available Prior to CRP: None.[7]
Sample Irradiations in CRP: JAERI (14.8 MeV).
Experimental Cross Sections from CRP: JAERI (14.8 MeV).
Nuclear Model Cross Sections from CRP: None.
Evaluations from CRP: IRK made an estimate of the cross section ≈ 14 MeV from systematics.
Status: Single experimental value from CRP is very uncertain because of possible Tb impurity in Dy sample, and cross section obtained conflicts with IRK estimate from systematics. Also, knowledge of the 14-MeV cross section alone is inadequate for such a low threshold reaction. Uncertainty remains very large in spite of CRP effort.

^{193}Ir(n,2n)^{192m2}Ir
Properties: Half life = 241 years. Threshold = 7.96 MeV. Decay = IT (100%). Dominant γ-ray = 317 keV (≈ 83%, from decay of ^{192g}Ir). There is a short-lived isomer (m1) as well as a medium-lived ground state (g) of ^{192}Ir involved in this reaction. The contribution of (m1+g) can be obtained by performing activity measurements relatively soon after the irradiation. Activity measurements made long after the irradiation yield only the m2 component.
Data Available Prior to CRP: A few values of the combined shorter-lived components (g+m1) exist.[7] Can estimate long-lived (m2) component from σ_{m2}(n,2n) = σ_{tot}(n,2n) - σ_{g+m1}(n,2n). Derive σ_{tot}(n,2n) from systematics. Large uncertainty due to neutron energy dependence and σ_{tot}(n,2n) derived from systematics.
Sample Irradiations in CRP: IAE/LU (14.2 MeV).
Experimental Cross Sections from CRP: IAE/LU (14.2 MeV).
Nuclear Model Cross Sections from CRP: LANL/LLNL, IPPE.
Evaluations from CRP: IRK made an estimate of the cross section ≈ 14 MeV from systematics. Nuclear model results evaluated at LLNL.
Status: The CRP effort generated a single experimental value and an estimate based on systematics, both ≈ 14 MeV. They are reasonably consistent. Combined with evaluated results from nuclear model calculations (normalized at 14.5 MeV), this information may satisfy the needs for fusion energy although the uncertainty remains significant.

^{187}Re(n,2n)^{186m}Re
Properties: Half life = 2 x 10^5 years. Threshold = 7.56 MeV. Decay = IT (100%). Dominant γ-ray = 59 keV (20%).
Data Available Prior to CRP: Some cross section values for the shorter-lived ground state component (g).[7] Can estimate long-lived (m) component from σ_m(n,2n) = σ_{tot}(n,2n) - σ_g(n,2n). Derive σ_{tot}(n,2n) from systematics. Large uncertainty due to neutron energy dependence and σ_{tot}(n,2n) derived from systematics.
Sample Irradiations in CRP: JAERI (14.8 MeV), IAE (14.2 MeV) KRI (13.5-14.9 MeV).
Experimental Cross Sections from CRP: JAERI (14.8 MeV), IAE (14.2 MeV).
Nuclear Model Cross Sections from CRP: DE, LANL/LLNL, IPPE.
Evaluations from CRP: IRK made an estimate of the cross section ≈ 14 MeV from systematics. Nuclear model results evaluated at LLNL.
Status: The cross sections derived from experiments appear to be very scattered and uncertain. Perhaps the samples from irradiations at JAERI, KRI and IAE can be counted after a longer cooling time (several years) to obtain consistent results. Until a reliable normalization ≈ 14 MeV becomes available, the overall status will remain very uncertain.

^{62}Ni(n,γ)^{63}Ni
Properties: Half life = 100.1 years. Threshold = None (exoergic reaction). Decay = β- (100%). No γ-rays.
Data Available Prior to CRP: Some values at low energy, mostly thermal.[7] Evaluated for ENDF/B-VI.[9]
Sample Irradiations in CRP: None.
Experimental Cross Sections from CRP: None.
Nuclear Model Cross Sections from CRP: DE.
Evaluations from CRP: None.
Status: No work done in CRP. It is necessary to rely mainly on the ENDF/B-VI isotopic evaluation which is based entirely on nuclear models. An assessment of the situation was made by IRK and it was concluded that the existing information is probably sufficient to satisfy fusion energy needs.

^{98}Mo(n,γ)^{99}Mo(β-)^{99}Tc(β-)^{99}Ru
Properties: Half life = 2.13 x 10^5 years. Threshold = None

(exoergic reaction). Decay = β- (100%, both steps). ^{99}Mo decays to both ^{99m}Tc and ^{99}gTc with known branching factors. ^{99}gTc is the long-lived species. No γ-rays are observed from ^{99}gTc decay, however ^{99m}Tc is relatively short-lived and decays ≈ 100% of the time to ^{99}gTc via IT (87.2% of these produce a γ-ray).
Data Available Prior to CRP: Some cross sections < 4 MeV.[7]
Sample Irradiations in CRP: SU (29-1100 keV), KRI (700-2000 keV).
Experimental Cross Sections from CRP: SU (29-1100 keV), KRI (700-2000 keV).
Nuclear Model Cross Sections from CRP: None.
Evaluations from CRP: None.
Status: The available coarse-resolution neutron capture data are in satisfactory agreement and they probably define the cross section adequately for fusion energy applications.

^{165}Ho(n,γ)^{166m}Ho
Properties: Half life = 1.2 x 10^{3} years. Threshold = None (exoergic reaction). Decay = β- (100%). Dominant γ-ray = 810 keV (64%).
Data Available Prior to CRP: Considerable cross section data for both total capture and capture to the shorter-lived ground state (g).[7] Can estimate long-lived (m) component from $\sigma_m(n,2n) = \sigma_{tot}(n,2n) - \sigma_g(n,2n)$.
Sample Irradiations in CRP: SU (674 keV).
Experimental Cross Sections from CRP: SU (674 keV).
Nuclear Model Cross Sections from CRP: LANL/LLNL.
Evaluations from CRP: None.
Status: Cross section, though rather uncertain, may be known well enough for fusion energy applications from the work of the CRP and existing results in the literature.

^{191}Ir(n,γ)^{192m2}Ir
Properties: Half life = 241 years. Threshold = None (exoergic reaction). Decay = IT (100%). Dominant γ-ray = 317 keV (≈ 83%, from decay of ^{192}gIr). There is a short-lived isomer (m1) as well as a medium-lived ground state (g) of ^{192}Ir involved in this reaction. The contribution of (m1+g) can be obtained by performing activity measurements relatively soon after the irradiation. Activity measurements made long after the irradiation yield only the m2 component.
Data Available Prior to CRP: Several data sets for both total capture and for g+m1. Could possibly estimate long-lived (m2) component from $\sigma_{m2}(n,\gamma) = \sigma_{tot}(n,\gamma) - \sigma_{g+m1}(n,\gamma)$. No effort within the CRP program has been made to explore this option.
Sample Irradiations in CRP: None.
Experimental Cross Sections from CRP: None.
Nuclear Model Cross Sections from CRP: None.
Evaluations from CRP: None.
Status: An estimate of the possible impact of this reaction on fusion energy applications has been made by IRK. Situation is unacceptable.