MEASURED FAST-NEUTRON ACTIVATION CROSS SECTIONS OF AG, CU, EU, FE, HF, NI, TB AND TI AT 10.3 AND 14.8 MEV AND FOR THE CONTINUUM NEUTRON SPECTRUM PRODUCED BY 7-MEV DEUTERONS ON A THICK BE-METAL TARGET*

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ABSTRACT

Four identical sample packets containing elemental Ag, Cu, Eu, Fe, Hf, Ni, Tb and Ti have been irradiated in three distinct accelerator neutron fields, at Argonne National Laboratory and Los Alamos National Laboratory, U.S.A., and Japan Atomic Energy Research Institute, Tokai, Japan, under the auspices of an International Atomic Energy Agency Coordinated Research Program to investigate the production of long-lived radionuclides for fusion waste disposal applications. Final experimental results are presented here for 13 distinct reactions which ultimately lead to production of the following activities: Ag-106m, 108m; Co-60g; Cr-51; Eu-150g, -152g; Hf-175, -179m2; Mn-54; Sc-46g, -47, -48; Tb-158g. The neutron fluence standard used was Ni-58(n,p)Co-58. The measured data include differential cross section values at 10.3 and 14.8 MeV, and integral cross sections for the continuum neutron spectrum produced by 7-MeV deuterons incident on a thick Be-metal target. The U-238(n,f) cross section was also measured at 10.3 MeV as a consistency check on the experimental technique. Some of the results of this study are compared with corresponding values from earlier work at Argonne and from ENDF/B-VI.

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1. INTRODUCTION

1.1 Background and Objectives

A recommendation was made at the 16th Meeting of the International Nuclear Data Committee (INDC), held in Beijing, People's Republic of China, 12-16 October 1987, to establish an International Atomic Energy Agency (IAEA) Coordinated Research Program (CRP) entitled "Measurements and Calculations of Activation Cross Sections for Long-lived Radionuclides Important for Radioactive Waste Estimates in Fusion Reactor Technology". This action followed from an earlier suggestion made by E. Cheng at the 1986 Gaussig Advisory Meeting on Nuclear Data for Fusion Reactor Technology [Cne88]. According to Cheng, the contemporary fusion reactor design studies call for operation at a very low rate of production of long-lived radionuclides, in order to minimize the problems of reactor maintenance, low-level waste disposal and, ultimately, reactor decommissioning. In order to meet these stringent requirements, cross section data are needed for activation reactions, not only for all the major structural constituents of fusion reactors, but also for the probable impurities. Consequently, the list of activation data needs spans nearly the entire periodic table. While some of these data requirements are familiar from fission-reactor technology, many are new because of the significant differences in these technologies, e.g. the higher average neutron energies that will be encountered in fusion machines. Current knowledge of the important cross sections varies from adequate to essentially unknown.

The IAEA concluded that formation of this CRP would provide a strong motivation to bring together the available technical resources required for addressing the problem. In order to provide a focus, the list of reactions to be considered by this CRP was limited to about a dozen. Argonne National Laboratory (ANL) was approached to participate in the project, along with various other organizations around the world. It was evident at the outset that intense sources of neutrons in the energy range of interest (< 15 MeV) would be needed in order to investigate these reactions experimentally. Such sources are generally limited to fission reactors (which are inappropriate for the present purposes), intense 14-MeV generators (not available at ANL), accelerator thick-target reactions such as $\text{Be}(d,n)$, and certain other special-purpose intense monoenergetic sources (e.g., the Los Alamos National Laboratory gas-target facility which employs the $\text{H}(t,n)$ reaction). ANL originally planned to conduct its investigations solely at the ANL FNG accelerator facility [CH71], employing the $\text{Be}(d,n)$ source [SMG85, SM86, Mea91] for its irradiations. It was suggested that this source, which provides an intense, continuum spectrum of neutrons with energies < 12 MeV, would provide useful cross section data at energies below 14 MeV, to complement the 14-MeV studies which were proposed by some of the other participants in the CRP. In particular, these data could shed light on the threshold regions for high-threshold reactions such as $(n,2n)$ processes. Subsequently, ANL decided to solicit a collaboration with the Japan

Atomic Energy Research Institute (JAERI) at Tokai, Japan (YI and CK). This laboratory had not been approached initially by the IAEA, but JAERI later expressed a strong interest in contributing the formidable JAERI experimental resources (in particular the FNS 14-MeV neutron source facility) to this effort. Finally, Los Alamos National Laboratory (LANL) also expressed a desire to participate in this work (RH), thereby bringing to the project its unique capability for producing intense, monoenergetic neutrons in the 5-13 MeV energy range via the $H(t,n)$ gas-target neutron source [HG90] at the LANL tandem accelerator facility [VMH74]. The LANL irradiations were performed at 10.3-MeV neutron energy for the present investigation.

A report on the progress of this investigation up to 1989 was presented at the first meeting of the CRP which was held at ANL in September 1989 [Mea+90]. Subsequently, a summary progress report on the activities of all participants in the CRP was presented at the Juelich Conference by Vonach [Von91]. The purpose of the present communication is to report some numerical results from the ANL/JAERI/LANL collaboration effort to date.

1.2 Scope of the Present Work

A careful review of the experimental resources available to the partners in this collaboration led us to decide to confine the investigation to certain activities which can be produced by neutron irradiation of the elements Ag, Eu, Hf and Tb. In addition, the elements Cu, Fe, Ni and Ti were included in the program because the cross sections for several reactions associated with these materials are reasonably well known and, therefore, afforded a check on the experimental procedures. Furthermore, these materials are also of interest for fusion applications. The neutron fluence standard chosen for the experiment was $Ni-58(n,p)Co-58$, a well-known dosimetry reaction. Table 1 lists the reactions specifically examined in this project. Table 2 provides essential decay parameters for the relevant activities associated with these processes. The choice of reactions to investigate in this work was restricted by limitations inherent to the experimental resources of the collaborators. In particular, certain longer-lived radionuclides of interest to the CRP could not be investigated because of insufficient available time (to date) to adequately eliminate the interference from shorter-lived components and/or insufficient neutron doses to the irradiated samples.

Some brief comments on the individual reactions from Table 1 are in order. First, no attempt was made to determine any cross sections for (n,γ) reactions. Interpretations of such data are very sensitive to detailed knowledge of the low-energy neutron spectra of the irradiation environments (see Section 3.2). Thus, the present work addresses only fast-neutron energies and threshold reactions. In fact, no specific effort was made to quantitatively examine any activities produced mainly by lower-energy neutrons other than what was required to apply corrections to the primary reaction data of this study. For Ag, both Ag-106g and Ag-106m are involved in the $(n,2n)$ reaction on Ag-107. Ag-106g was not investigated because of its short half life.

Ag-106m decays to Pd-106, not to Ag-106g. Consequently, the measured cross section accounts only for excitation of the isomer and those energetically accessible levels which feed it. A similar situation exists in the formation of Ag-108. Both Co-60g and Co-60m are involved in the (n,a) reaction on Cu-63. Since Co-60m decays with a moderately short half life to Co-60g, the present experiment yields a cross section for excitation of all energetically accessible levels in Co-60. Similar comments can be made for Sc-46 and Co-58, which are produced by (n,p) reactions on Ti and Ni, respectively, and for Tb-158 which is generated by the (n,2n) reaction on Tb-159. Eu-150g and Eu-150m are produced by the (n,2n) reaction on Eu-151. However, the isomer decays with a relatively short half life to adjacent nuclei. There are no isomeric transitions to Eu-150g. Consequently, the present experiment measures only the excitation of Eu-150g and those levels which feed it. For Eu-152, the situation is more complicated. The ground state and two isomers are involved. However, the first isomer (m1) is isolated owing to a relatively short half life and a decay scheme which precludes transitions to Eu-152g. The second isomer (m2) feeds only Eu-152g by isomeric transitions, bypassing the first isomer. Therefore, the cross section measured in this work includes only levels which feed the ground state or m2. For Hf-179, the ground state is stable so its direct formation rate by the (n,2n) reaction is not measurable by activation. There are two isomers involved. The first isomeric state (m1) has a very short half life and was not measured. Furthermore, the second isomer (m2) decays ultimately to the ground state, bypassing m1. Consequently, only the yield of m2 and those levels which feed it is measured in this experiment. Finally, there are no isomeric levels involved in Cr-51, Hf-175, Mn-54, Sc-47 and Sc-48 so the present measurements include the strength for all energetically-accessible levels in these nuclei.

2. EXPERIMENTAL PROCEDURES

2.1 Samples

It was essential for the success of this experiment to accumulate the maximum possible neutron doses for each of the sample materials within the available irradiation times. Therefore, it was decided to employ sample packets that included all of the materials of interest for this work. Several identical sample packets of this nature were assembled for the experiment, as shown in Fig. 1. These packets were nominally 2.54 cm in diameter and ≤ 2 cm thick. The Eu, Hf and Tb samples were represented in the form of oxides, since these rare-earth elements are quite reactive in the natural state. The oxides were encapsulated in sealed plastic containers which defined the sample geometries and prevented any loss of material. All the other sample materials were in the form of metal foils. The chemical purity of all samples was $> 99.9\%$ and the isotopic abundances were standard elemental (see Table 1). Table 3 lists some of the other important sample parameters. Five Ni foils were included in each sample packet to measure the total neutron fluences and associated fluence gradients

in the irradiation environments seen by these packets (see Fig. 1).

2.2 Irradiation Procedures

The irradiation at ANL was carried out using the Be(d,n) thick-target neutron spectrum [SMG85,SM86,Mea91] produced by 7-MeV deuterons from the ANL FNG accelerator [CH71] incident on a thick Be-metal target. The neutron spectrum is a continuum ranging from < 0.1 MeV up to about 11.4 MeV. The sample packet occupied a position on the beam line (zero deg) in the range 5 - 7 cm from the Be target. This experiment was entirely passive in the sense that no data were recorded in real time with instrumented radiation detectors. The neutron fluences were deduced solely from Co-58 activity measurements performed for each of the five Ni monitor foils contained in the sample packet, thereby utilizing the Ni-58(n,p)Co-58 reaction as a standard (see Table 1.). The irradiation consisted of about 110 hours of cumulative exposure, occurring over a period of nearly a month during November and December 1988. The accumulated neutron fluence at the sample position was $\sim 1\text{-}2 \times 10^{15}$ n/cm².

The measurement at LANL utilized a 15.75-MeV triton beam from the tandem accelerator [VMH74] and a rotating hydrogen-gas-target assembly [HG90] to produce neutrons via the H(t,n) source reaction. The gas volume of this target extended 4.6-cm along the beam line (zero deg). The sample packet used in this irradiation occupied a position on the beam line which was stated to be in the range 4 - 6 cm from the gas target. However, in subsequent analysis of the data, it was found that an effective distance of 5 - 7 cm had to be assumed in order to obtain consistent results for the Ni monitor foils (see Section 3.1). This arrangement yielded a calculated mean neutron energy of 10.3 MeV with a corresponding resolution of about 0.4 MeV. A fission chamber was also employed during these irradiations as an auxiliary neutron monitor. This detector contained a uranium deposit (identified as U-238-26 in Ref. Mea90) with a total mass of 950 ± 60 μ g of material. Its isotopic composition was: U-238 (99.585%), U-235 (0.415%). Other uranium isotopes were negligible. About 14 hours of total beam time were devoted to this experiment, occurring during two irradiation periods in October and November 1988. The accumulated neutron fluence at the sample position was $\sim 2\text{-}3 \times 10^{13}$ n/cm².

Two sample packets were irradiated in June 1989 at the JAERI FNS accelerator facility [Nak+82]. These were placed at two symmetric positions located at 43 deg relative to the incident beam line and 7 cm from the target. The mean energy for the neutrons impinging on each sample was 14.8 MeV with a resolution of about 0.5 MeV. A total of 32 hours (divided into four 8-hour intervals) of beam time was allocated to the experiment. The accumulated neutron fluence at the sample position was $\sim 1\text{-}2 \times 10^{14}$ n/cm². Like the ANL experiment, this irradiation was passive and relied on the Ni dosimeter foils for determination of neutron fluences. One of the sample packets was retained at JAERI for activity counting and subsequent data analysis. The results of this investigation are reported elsewhere [Ike+91]. The present communication deals only with results derived from the sample

packet which was sent back to ANL after the irradiation at JAERI, for counting and analysis.

2.3 Activity Measurements

With the exception of one sample packet which remained at JAERI, all the irradiated samples were counted at ANL. In each instance, the gamma-ray activities were measured with germanium detectors whose efficiencies had been calibrated by conventional techniques (e.g., Ref. MS84) using standard gamma-ray sources (e.g., from the National Institute of Standards and Technology). Full-energy peak yields were determined from recorded gamma-ray spectra. At early counting times following the irradiations, these spectra were dominated by shorter-lived components. Peaks corresponding to longer-lived activities could only be measured after the passage of many months following the irradiations. Some activities which might ultimately be measurable in these samples remain to be investigated. Several years will be needed to arrive at the proper counting conditions, so this work will have to be deferred to a later date. Table 2 provides a summary of the important parameters associated with various activities which have been studied up to the present time. This information was derived from the available documented compilations and/or evaluations of such data (e.g., the Nuclear Data Sheets), as indicated in the footnotes to Table 2. In some cases, several gamma-ray lines attributed to the same decay activity were analyzed. For compactness, Table 2 provides information only on the dominant transition in these instances.

3. DATA ANALYSIS

3.1 Procedures and Data Corrections

The raw activation data were processed using conventional experimental techniques (e.g., see Refs. SM73, SMB85, GSM89, Smi+91). The numbers of target atoms in each of the samples were determined from the known sample masses, atomic masses, isotopic abundances (see Table 1), and chemical compositions of the irradiated materials. The gamma-ray counting data were converted to reaction product yields using calibrated detector efficiencies, decay branching parameters (see Table 2), and activity-decay factors based on tabulated half lives (see Table 2). Other corrections to the counting data were applied as needed (e.g., geometry factors, coincidence summing, etc.). The fission detector events which were recorded during the LANL experiment were corrected for spectrum extrapolation and fission-deposit thickness losses. The data from LANL were also corrected for empty cell contributions to the fission detector counts and sample activities. These latter corrections were calculated from available spectral data and differential cross sections, since empty-cell measurements were not explicitly performed in this investigation. Finally, corrections were applied to all the data to account for irradiation geometry effects, neutron source properties,

neutron absorption and neutron multiple scattering. It is interesting to note that the activation data for the five Ni monitor foils included in each sample packet were very consistent after application of all these corrections. The standard deviations for the five individual foils relative to the mean were as follows for the three irradiations of this experiment: ANL, Be(d,n) - 1.6%; LANL, 10.3 MeV - 0.7%; JAERI, 14.8 MeV - 0.6%. As mentioned in Section 2.2, a change had to be made in the assumed distance of the sample from the gas target in the LANL measurements (from 4 - 6 cm to 5 - 7 cm) in order to achieve the consistency quoted above. No other plausible explanation could be found to explain the discrepancy which would have existed otherwise. Cross section ratios relative to the Ni-58(n,p)Co-58 standard reaction were obtained from the adjusted results and, ultimately, experimental cross sections were derived using appropriate values for the Ni-58(n,p)Co-58 cross section. In the case of the Be(d,n) spectrum irradiations at ANL, it was necessary to calculate a value for the spectrum-averaged Ni-58(n,p)Co-58 standard cross section from the ENDF/B-VI differential cross section values and an appropriate representation of the Be(d,n) continuum neutron spectrum. Recent results from Meadows [Mea91] were employed for the spectrum representation in this analysis.

3.2 Interfering Activities

Interpretation of the measured data for four of the $(n,2n)$ reactions considered in this work was complicated by interference from (n,γ) capture-activation processes on other target isotopes in the elemental samples. These (n,γ) reactions could produce sample activities which were indistinguishable from those generated by the primary $(n,2n)$ processes. The (n,γ) cross section is quite small in the MeV region so this process usually causes no serious problems in the measurement of the much larger $(n,2n)$ cross sections for fast neutrons. However, in the radiation environments of the present investigation, particularly those at ANL and LANL, there were room-return neutrons present at thermal and epithermal energies which, in spite of their relatively modest numbers, were troublesome because the afflicted materials have rather large thermal capture cross sections and resonance capture integrals. Fortunately, there were other activities present in some of the samples which could be attributed only to neutron capture reactions, and these could be used to estimate corrections to the other data for (n,γ) events. For the purpose of evaluating these needed corrections, estimates were made of the thermal and resonance-region neutron fluences from the observed yields of the activities produced solely by neutron capture. These deduced effective neutron fluences were then used to compute required corrections to the $(n,2n)$ data for (n,γ) interferences by means of the thin-absorber approximation. The samples involved are by no means thin, but fairly consistent results were obtained. Since this entire procedure is not a very exact one, it was decided not to report explicitly any experimental (n,γ) cross sections from the present investigation (see Section 1.2). The capture-activation correction was largest for $\text{Eu-153(n,2n)Eu-152g+m2}$. That activity specifically due to $\text{Eu-151(n,\gamma)}$ amounted to about 12% for the JAERI irradiations and, in

the case of the ANL and LANL exposures, substantially exceeded the primary contributions from the $(n,2n)$ reaction. In fact, these latter corrections were so large that the $(n,2n)$ cross section values we deduced for these two irradiation environments are quite speculative at best. Therefore, we decided not to report them here. In contrast, the corrections for Ag-109($n,2n$)Ag-108m and Hf-176($n,2n$)Hf-175, due to Ag-107(n,γ) and Hf-177(n,γ), respectively, were quite modest ($< 7\%$), and that for Hf-180($n,2n$)Hf-179m2 due to Hf(n,γ) was essentially negligible.

4. RESULTS AND DISCUSSION

4.1 Experimental Cross Sections

The cross sections obtained from the present experiment are presented in Table 4. The obvious deficiencies of this table are attributable to specific circumstances relating to activity decay, interfering activities, etc., which made it impossible to determine reliable cross section values. Estimates were made of the contributions from various conventional sources of error in these measurements. These errors are listed in Tables 5 - 7. The composite errors also appear in Table 4. We believe that these quoted errors are essentially lower bounds on the total experimental error, and they do explicitly exclude the standard cross section errors. In the case of the Be(d,n) measurements, it was necessary to include a representation of the continuum neutron spectrum in the analysis in order to provide a value for the standard integral cross section for Ni-58(n,p)Co-58. The spectral representation from Meadows [Mea91] was employed for this purpose. All references to Ni-58(n,p)Co-58 differential cross sections are based on ENDF/B-VI [ENDF90].

4.2 Comparisons with Other Corresponding Available Results

The main purpose of this communication is to thoroughly document the results from our work so that they can be properly compared with other results from the CRP project. Up to this point, we have not undertaken a comprehensive search of the relevant literature for reactions leading to long-lived radionuclides because we believe that it would be premature to do so before all the other data from the CRP are available. However, it is of interest to compare the present results for the better known reactions with some other recent values from the literature, in order to assess the reliability of our experimental procedures. To this end, we have compared certain Be(d,n) results with corresponding values obtained from earlier work at ANL [SMG90]. The outcome is documented in Table 8. We find that the agreement is generally pretty good for the Cu and Fe reactions but not as good, overall, for the Ti reactions. There is a good reason why the quality of the present results for Ti-47,48(n,p) should be inferior to the corresponding earlier ANL results. As indicated in Section 2.2, the exposure time for the irradiated sample packet amounted to nearly a month. We undertook as long an exposure time as the circumstances

allowed in order to enhance the yield of the sought-after long-lived activities. This irradiation period exceeded the half lives for Sc-47 and Sc-48 by at least an order of magnitude. The decay corrections that had to be applied to these data to obtain cross sections were very large and, consequently, the results are quite sensitive to the exact details of the irradiation history. This lends considerable uncertainty to the resultant cross sections for these reactions, which is probably only partially reflected in the quoted errors.

A comparison was also made of some of the present results with corresponding evaluated values based on ENDF/B-VI [ENDF90], as shown in Table 9. As mentioned above, the Be(d,n) spectrum representation from Meadows [Mea91] was employed in comparing the integral results. Once again, the overall agreement is fairly good for Cu and Fe and not as good for Ti. A probable reason for Ti-47,48(n,p) has already been discussed in the preceding paragraph. However, it is not clear at this time as to why there is a discrepancy for the 14.8-MeV cross section of Ti-48(n,p).

4.3 Future work

There remains the possibility that data can eventually be acquired for the Cu-63(n,p)Ni-63 (100.1 y) and Hf-179(n,2n)Hf-178 (31 y) reactions. These two reactions appeared in the original CRP list but have not been addressed in the present work. In the case of Ni-63, it will be necessary to rely on alternative counting procedures since there are no gamma rays associated with Ni-63 decay. For us, it is mainly a matter of finding support for this work, or finding a willing collaborator who is already equipped to perform the necessary activity measurements. In the case of Hf, we intend to recount the samples in the near future to see if it will be possible to observe and measure the 31-y activity which was previously masked by shorter-lived components.

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Table 1: Reactions Considered in the Present Work

<u>Reaction</u>	<u>Target Isotopic Abundance (%)^a</u>	<u>Q-value (MeV)^a</u>
Ag- 107(n,2n)Ag- 106m	51.839±0.005	- 9.637
Ag- 109(n,2n)Ag- 108m	48.161±0.005	- 9.300
Cu- 63(n, α)Co- 60g+m	69.17±0.02	1.715, 1.656*
Eu- 151(n,2n)Eu- 150g	47.8±0.5	- 7.965
Eu- 153(n,2n)Eu- 152g+m2	52.2±0.5	- 8.551, - 8.699*
Fe- 54(n,p)Mn- 54†	5.9±0.2	0.086
Fe- 54(n, α)Cr- 51†	5.9±0.2	0.843
Hf- 176(n,2n)Hf- 175†	5.206±0.004	- 8.091
Hf- 180(n,2n)Hf- 179m2	35.100±0.006	- 8.495
Tb- 159(n,2n)Tb- 158g+m	100	- 8.132, - 8.242*
Ni- 58(n,p)Co- 58g+m§	68.077±0.005	0.402, 0.377*
Ti- 46(n,p)Sc- 46g+m	8.0±0.1	- 1.584, - 1.727*
Ti- 47(n,p)Sc- 47†	7.3±0.1	0.182
Ti- 48(n,p)Sc- 48†	73.8±0.1	- 3.207
U- 238(n,f)	Enriched deposit#	NA‡

* Multiple Q-values correspond to the ground state and those indicated isomeric levels which are included in the measured cross section.

† There are no isomeric states in this nucleus.

§ Reaction cross-section standard for this experiment.

See Section 2.2 of the text.

‡ NA = Not applicable.

^a Ref. Tul90.

Table 2: Decay Properties of the Radioactive Nuclei Involved in the Present Work

<u>Activity</u>	<u>Jπ</u>	<u>Excitation Energy (MeV)</u>	<u>Half Life*</u>	<u>Decay Mode#</u>	<u>Measured γ Ray (MeV)</u>	<u>Relevant γ Branch (%)</u>
Ag-106m ^a	6+	0.090	8.46 $\pm$ 0.10 d	EC, (β^+)	0.512	87.7 $\pm$ 0.5
Ag-108m ^b	6+	0.109	418 $\pm$ 12 y ^o	EC, β^+ , IT	0.434	90.5 $\pm$ 0.6
Co-58g ^c	2+	g.s.	70.82 $\pm$ 0.03 d	EC, β^+	0.811	99.448 $\pm$ 0.008
Co-58m ^{†c}	5+	0.025	9.15 $\pm$ 0.10 h.	IT	NA [†]	NA
Co-60g ^d	5+	g.s.	5.2714 $\pm$ 0.0005 y	β^-	1.333	99.982 $\pm$ 0.001
Co-60m ^{†d}	2+	0.059	10.47 $\pm$ 0.04 m	IT, (β^-)	NA	NA
Cr-51 $\S^e$	7/2-	g.s.	27.702 $\pm$ 0.004 d	EC, (β^+)	0.320	10.08 $\pm$ 0.23
Eu-150g ^f	5-	g.s.	35.8 $\pm$ 1.0 y	EC, (β^+)	0.334	96 $\pm$ 3
Eu-152g ^g	3-	g.s.	13.542 $\pm$ 0.010 y	EC, β^+ , β^-	0.344	27.6 $\pm$ 0.3
Eu-152m ^{†g}	8-	0.148	96 $\pm$ 1 m	IT, (β^-)	NA	NA
Hf-175 $\S^h$	5/2-	g.s.	70 $\pm$ 2 d	EC	0.343	87.0 $\pm$ 0.5
Hf-179m ²ⁱ	25/2-	1.106	25.1 $\pm$ 0.3 d	IT	0.454	68.6 $\pm$ 3.6
Mn-54 $\S^j$	3+	g.s.	312.12 $\pm$ 0.10 d	EC, (β^+)	0.835	99.976 $\pm$ 0.001
Sc-46g ^k	4+	g.s.	83.810 $\pm$ 0.010 d	β^-	0.889	99.984 $\pm$ 0.001
Sc-46m ^k	1-	0.143	18.75 $\pm$ 0.04 s	IT	NA	NA
Sc-47 $\S^l$	7/2-	g.s.	3.345 $\pm$ 0.003 d	β^-	0.159	67.9 $\pm$ 1.5
Sc-48 $\S^m$	6+	g.s.	43.7 $\pm$ 0.1 m	β^-	0.984	100
Tb-158g ⁿ	3-	g.s.	180 $\pm$ 11 y	EC, β^+ , β^-	0.944	43.9 $\pm$ 1.3
Tb-158m ⁿ	0-	0.110	10.5 $\pm$ 0.2 s	IT	NA	NA

* s (second), m (minute), h (hour), d (day), y (year).

Decay branches marked by (...) are negligibly weak.

† Isomeric activity not measured directly in this investigation. Decay contributes indirectly to the measured ground state activity.

‡ NA: Not applicable.

§ There are no isomeric states for this nucleus.

^a Ref. Fre88 ^e Ref. Chu91 ⁱ Ref. Bro88 ^m Ref. Alb85

^b Ref. Bla91 ^f Ref. Mat86 ^j Ref. GJJ87 ⁿ Ref. Lee89

^c Ref. Pek90 ^g Ref. Pek89 ^k Ref. Alb86 ^o Ref. SSD91

^d Ref. AEL86 ^h Ref. Min76 ^l Ref. Bur86

Table 3: Properties of Sample Materials in the Irradiation Packets

<u>Element</u>	<u>Chemical Form</u>	<u>Mass (gram)†</u>	<u>Nominal Sample Dimensions (cm)‡</u>
Ag	Element (metal)	2.715-2.742	2.54 dia x 0.0508 thick
Cu	Element (metal)	1.1630-1.1744	2.54 dia x 0.0254 thick
Eu	Oxide (powder)	1.057-1.223	2.06 dia x 0.3175 thick§
Fe	Element (metal)	1.9101-2.0316	2.54 dia x 0.0508 thick
Hf	Oxide (powder)	2.879-3.184	2.06 dia x 0.3175 thick§
Ni	Element (metal)	1.1319-1.1471	2.54 dia x 0.0254 thick
Tb	Oxide (powder)	1.864-2.498	2.06 dia x 0.3175 thick§
Ti	Element (metal)	0.5455-0.5761	2.54 dia x 0.0254 thick

† Range of masses encountered for individual samples of this type.

‡ Exact dimensions vary somewhat from sample to sample.

§ These are the approximate dimensions of the oxide region itself. The overall dimensions of the sample, including the encapsulating material, are approximately 2.54 dia x 0.476 cm thick. See Fig. 1.

Table 4: Experimental Cross Sections Obtained from this Investigation

Reaction	Cross Section (millibarn)*		
	Be(d,n)†	10.3 MeV#	14.8 MeV@
Ag-107(n,2n)Ag-106m	1.03 (± 4.9%)	11.6 (± 4.4%)	NA‡
Ag-109(n,2n)Ag-108m	NA‡	40.8 (± 8.5%)	734 (± 3.9%)
Cu-63(n, α)Co-60g+m	2.01 (± 2.2%)	29.1 (± 4.7%)	43.5 (± 2.2%)
Eu-151(n,2n)Eu-150g	15.7 (± 5.8%)	198 (± 7.9%)	1282 (± 5.8%)
Eu-153(n,2n)Eu-152g+m2	NA‡	NA‡	1909 (± 7.4%)
Fe-54(n,p)Mn-54	185 (± 2.4%)	447 (± 3.1%)	306 (± 2.9%)
Fe-54(n, α)Cr-51	3.43 (± 2.5%)	40.8 (± 4.9%)	92.8 (± 2.5%)
Hf-176(n,2n)Hf-175	39.6 (± 5.0%)	1139 (± 7.2%)	2100 (± 5.0%)
Hf-180(n,2n)Hf-179m2	2.63 (± 7.7%)	24.7 (± 8.5%)	24.9 (± 7.1%)
Tb-159(n,2n)Tb-158g+m	28.0 (± 9.6%)	536 (± 9.8%)	2110 (± 7.9%)
Ti-46(n,p)Sc-46g+m	37.7 (± 2.2%)	255 (± 5.2%)	321 (± 2.2%)
Ti-47(n,p)Sc-47	34.8 (± 6.1%)	NA‡	NA‡
Ti-48(n,p)Sc-48	1.50 (± 7.1%)	NA‡	NA‡
U-238(n,f)	NA‡	1064 (± 6.5%)§	NA‡

* Absolute cross sections are derived from the following standard cross section values for the Ni-58(n,p)Co-58g+m reaction: Be(d,n) - 240 millibarn; 10.3 MeV - 589 millibarn; 14.8 MeV - 320 millibarn [ENDF90]. The errors are obtained from Tables 5-7. Errors in the applicable standard cross sections are not included.

† ANL irradiation (Section 2.2). Standard integral cross section value based on the Be(d,n) spectrum representation from Meadows [Mea91].

LANL irradiation (Section 2.2).

@ JAERI irradiation (Section 2.2).

‡ NA = Not measured in the present investigation.

§ Includes a 6.3% fission-deposit mass error [Mea90] in addition to the error obtained from Table 6.

Table 5: Examined Error Sources for the Be(d,n) Spectrum Measurements

Reaction	Estimated Error Component (%)							(n, γ)*	Total Error
	γ Yield	Half Life	γ Branch	Activ. Decay	Geom.	Neut. Trans.	Mult. Scat.		
Ag-107(n,2n)	2.3	0.1	0.6	4.2	0.1	0.1	0.6	NA†	4.9
Ag-109(n,2n)				--- NA ---					
Cu-63(n, α)	2.2	Neg‡	Neg	0.1	Neg	0.1	0.3	NA	2.2
Eu-151(n,2n)	4.0	2.8	3.1	Neg	0.3	0.1	0.4	NA	5.8
Eu-153(n,2n)				--- NA ---					
Fe-54(n,p)	2.0	Neg	Neg	0.5	Neg	0.1	1.2	Neg	2.4
Fe-54(n, α)	2.5	Neg	Neg	1.4	Neg	0.1	0.3	NA	2.9
Hf-176(n,2n)	2.1	2.9	0.6	Neg	0.3	0.1	0.3	3.4	5.0
Hf-180(n,2n)	5.5	1.2	5.2	1.0	0.3	0.1	0.3	Neg	7.7
Tb-159(n,2n)	6.8	6.1	3.0	Neg	0.3	0.1	0.4	NA	9.6
Ti-46(n,p)	2.1	Neg	Neg	0.1	Neg	0.1	0.6	NA	2.2
Ti-47(n,p)	2.2	0.1	1.2	5.4	Neg	0.1	1.3	NA	6.1
Ti-48(n,p)	2.6	0.2	Neg	6.6	Neg	0.1	0.2	NA	7.1
U-238(n,f)				--- NA ---					

* See Section 3.2.

† NA = Not applicable.

‡ Neg = Negligible (< 0.1%).

Table 6: Examined Error Sources for the 10.3-MeV Measurements

Reaction	Estimated Error Component (%)								Empty Cell	Total Error
	γ Yield	Half Life	γ Branch	Activ Decay	Geom	Neut Trans	Mult Scat	(n, γ)*		
Ag-107(n,2n)	2.6	0.1	0.6	2.1	0.1	0.1	0.5	NA†	2.7	4.4
Ag-109(n,2n)	7.4	2.9	0.6	0.7	0.1	0.1	0.5	1.2	2.7	8.5
Cu-63(n, α)	2.2	Neg‡	Neg	Neg	0.1	0.1	0.7	NA	4.1	4.7
Eu-151(n,2n)	2.8	2.8	3.1	0.7	3.3	0.1	0.8	NA	5.0	7.9
Eu-153(n,2n)				---	NA	---				
Fe-54(n,p)	2.1	Neg	Neg	0.5	0.1	0.1	0.3	NA	2.2	3.1
Fe-54(n, α)	2.7	Neg	Neg	0.8	0.1	0.1	0.7	NA	3.9	4.9
Hf-176(n,2n)	2.2	2.9	0.6	0.7	3.3	0.1	0.3	0.4	5.2	7.2
Hf-180(n,2n)	2.4	1.2	5.2	0.9	3.3	0.1	0.3	Neg	5.2	8.5
Tb-159(n,2n)	3.1	6.1	3.0	0.7	3.3	0.1	0.3	NA	5.4	9.8
Ti-46(n,p)	2.3	Neg	Neg	3.8	0.2	0.1	0.8	NA	2.5	5.2
Ti-47(n,p)				---	NA	---				
Ti-48(n,p)				---	NA	---				
U-238(n,f)	NA	NA	NA	NA	Neg	0.1	1.2	Neg	1.2	1.7

* See Section 3.2.

† NA = Not applicable.

‡ Neg = Negligible (< 0.1%).

Table 7: Examined Error Sources for the 14.8-MeV Measurements

Reaction	Estimated Error Component (%)								Total Error
	γ Yield	Half Life	γ Branch	Activ. Decay	Geom.	Neut. Trans.	Mult. Scat.	(n, γ)*	
Ag-107(n,2n)				--- NA† ---					
Ag-109(n,2n)	2.2	2.9	0.6	0.2	1.3	0.1	0.4	Neg‡	3.9
Cu-63(n, α)	2.2	Neg	Neg	0.2	0.1	0.1	0.4	NA	2.2
Eu-151(n,2n)	2.1	2.8	3.1	0.2	3.4	0.1	0.7	NA	5.8
Eu-153(n,2n)	2.3	0.1	1.1	0.2	3.4	0.1	0.7	6.0	7.4
Fe-54(n,p)	2.2	Neg	Neg	0.2	0.1	0.1	0.4	NA	2.2
Fe-54(n, α)	2.5	Neg	Neg	0.2	0.1	0.1	0.2	NA	2.5
Hf-176(n,2n)	2.1	2.9	0.6	0.6	3.4	0.1	0.3	Neg	5.0
Hf-180(n,2n)	3.1	1.2	5.2	0.5	3.4	0.1	0.3	Neg	7.1
Tb-159(n,2n)	2.1	6.1	3.0	0.2	3.4	0.1	0.5	NA	7.9
Ti-46(n,p)	2.1	Neg	Neg	0.3	0.2	0.1	0.7	NA	2.2
Ti-47(n,p)				--- NA ---					
Ti-48(n,p)				--- NA ---					
U-238(n,f)				--- NA ---					

* See Section 3.2.

† NA = Not applicable.

‡ Neg = Negligible (< 0.1%).

Table 8: Comparison of Present Results with Previously Reported Experimental Values from ANL for Selected Be(d,n) Integral Cross Sections

<u>Reaction</u>	Integral Cross Section (millibarn)*		<u>Ratio</u>
	<u>Present†</u>	<u>Previous Work^a</u>	
Cu-63(n, <i>a</i>)Co-60g+m	2.01 (± 2.2%)	1.90 (± 7.3%)	1.06
Fe-54(n,p)Mn-54	185 (± 2.4%)	193 (± 4.8%)	0.96
Fe-54(n, <i>a</i>)Cr-51	3.43 (± 2.9%)	3.23 (± 10.5%)	1.06
Ti-46(n,p)Sc-46g+m	37.7 (± 2.2%)	34.0 (± 4.6%)	1.11
Ti-47(n,p)Sc-47	34.8 (± 6.1%)	40.4 (± 6.7%)	0.86
Ti-48(n,p)Sc-48	1.50 (± 7.1%)	1.16 (± 6.5%)	1.29

* Errors are those appearing in the original cross-section tables.

† ANL irradiation (Section 2.2). Standard integral cross section value based on the Be(d,n) spectrum representation from Meadows [Mea91]. See Table 4.

^a Ref. SMG90.

Table 9: Comparison of Selected Present Cross Section Results with Corresponding Evaluated Values from ENDF/B-VI

Reaction	Cross Section (millibarn)								
	Be(d,n) [#]			10.3 MeV			14.8 MeV		
	<u>Exp.</u> [*]	<u>Eval.</u> [†]	<u>Rat.</u> [‡]	<u>Exp.</u>	<u>Eval.</u>	<u>Rat.</u>	<u>Exp.</u>	<u>Eval.</u>	<u>Rat.</u>
Cu-63(n, α)	2.01	1.77	1.14	29.1	32.5	0.90	43.5	38.8	1.12
Fe-54(n,p)	185	184	1.01	447	471	0.95	306	306	1.00
Fe-54(n, α)	3.43	3.06	1.12	40.8	56.8	0.72	92.8	87.5	1.06
Ti-46(n,p)	37.7	33.1	1.14	255	249	1.02	321	250	1.28
Ti-47(n,p)	34.8	45.9	0.76	NA [§]	134	---	NA	112	---
Ti-48(n,p)	1.50	1.08	1.39	NA	33.7	---	NA	63.0	---
U-238(n,f)	NA	461 ^a	---	1064	989	1.08	NA	1176	---

[#] ANL irradiation (Section 2.2). Standard integral cross section value based on the Be(d,n) spectrum representation from Meadows [Mea91].

^{*} See Table 4.

[†] Ref. ENDF90.

[‡] Ratio = experimental cross section $\div$ evaluated cross section

[§] NA = Not available.

^a Obtained from SMG90.

Fig. 1: Schematic diagram for the identical sample packets used in each of the neutron irradiations. The sample materials are as follows: a = Ni(#1), b = Ag, c = Ni(#2), d = HfO_2 , e = Ni(#3), f = Tb_4O_7 , g = Ni(#4), h = Eu_2O_3 , i = Ni(#5), j = Cu, k = Fe, l = Ti. The oxide samples (indicated by the shaded regions) are contained in plastic capsules.

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