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RESULTS FROM THE ARGONNE, LOS ALAMOS, JAERI COLLABORATION[a]

J. Meadows and D. Smith, Engineering Physics Division
L. Greenwood[b], Chemical Technology Division
Argonne National Laboratory
Argonne, Illinois 60439, U.S.A.

R. Haight, Physics Division
Los Alamos National Laboratory
Los Alamos, New Mexico 87545, U.S.A.

Y. Ikeda and C. Konno, Reactor Engineering Department
Japan Atomic Energy Research Institute
Tokai-mura, Naka-gun, Ibaraki-ken 319-11, Japan

ABSTRACT

Four sample packets containing elemental Ti, Fe, Ni, Cu, Nb, Ag, Eu, Tb and Hf 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. The acquired experimental data include differential cross sections (at 10.3 and 14.7 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. This is the third progress report on a project which has been carried out under the auspices of an IAEA Coordinated Research Program entitled "Activation Cross Sections for the Generation of Long-lived Radionuclides of Importance in Fusion Reactor Technology". The present report provides the latest results from this work. Comparison is made between the 14.7-MeV cross-section values obtained from the separate investigations at Argonne and JAERI. Generally, good agreement is observed within the experimental errors when consistent sample parameters, radioactivity decay data and reference cross values are employed. A comparison is also made between the experimental results and those derived from calculations using a nuclear model. Experimental neutron information on the Be(d,n) neutron spectrum was incorporated in the comparisons for the integral results. The agreement is satisfactory considering the various uncertainties that are involved.

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[b] Present address: Battelle Pacific Northwest Laboratories, Richland, Washington 99352.

1. INTRODUCTION

The objectives and details of this experiment have been presented in two earlier reports in this series which were prepared at Argonne [Mea+90,Mea+91] and in corresponding reports from JAERI [IK91,Ike+91]. There is no need to repeat these discussions here. Additional information on the method of analysis employed at JAERI is documented in another report from that laboratory [Ike+88]. Since 1991, attention has been paid to selection of a common set of sample parameters, radioactivity decay data and reference standards in order to consolidate individual contributions from the participants in this research program. It was decided to reject all data associated with the Eu-153(n,2n)Eu-152g+m2 reaction since it was concluded, from independent analyses conducted at JAERI and Argonne, that the corrections necessitated by (n,γ) reactions on Eu-151 were too large to permit a reliable determination of the (n,2n) cross section for Eu-153. Separated-isotope samples will be needed to do a proper job of determining this cross section. The results for Ti-47(n,p)Sc-47 and Ti-48(n,p)Sc-48 have also been discarded because of the large uncertainties associated with requisite decay correction factors for the relatively short-lived Sc-47 and Sc-48 activities. The work at JAERI produced cross sections for the reactions Ni-60(n,p)Co-60g+m and Hf-179(n,2n)Hf-178m2 which were not obtained from the Argonne investigation. The reason for this is that it was possible at JAERI to re-count the samples after the shorter-lived, interfering activities had died away, whereas this was not possible at Argonne because the research program was terminated there and the experimental facilities employed in the Argonne activity measurements were dismantled in 1992.

For completeness, most of the tabular material provided in the second Argonne report [Mea+91] is included here, with some alterations in form and content as needed to account for changes in the parameters and methods of analysis which have occurred since 1991. Table 1 describes the samples used in the experiment. Niobium foils were placed at the front and back of the sample packet which was irradiated at JAERI and retained there for analysis. The other three sample packets did not include niobium. Table 2 lists the reactions considered, the relevant isotopic abundances and the pertinent reaction Q-values. Table 3 summarizes the pertinent radioactive-decay properties of the reaction products. Modifications in the analyses carried out at both JAERI and Argonne since 1991 have led to significant revisions of the cross section values reported earlier [Mea+91,Ike+91,IK91]. A notable change for the JAERI irradiations was a revision of the effective neutron energy, from 14.8 MeV to 14.7 MeV. The present results correspond to use of a common set of sample parameters, radioactive decay data and reference cross section values. The 14.7-MeV cross section results from Argonne and JAERI now are entirely based on a value of 292 ± 7 mb for the Ni-58(n,p)Co-58g+m reference cross section at this energy. This cross section is derived from earlier studies carried out at JAERI [Ike+88]. Its use leads to very good overall consistency in neutron fluence determinations, when taken in conjunction with the value 459 ± 11 mb for the Nb-93(n,2n)Nb-92m secondary reference cross section (see Table 4). Unlike the investigation at JAERI, the analysis carried out at Argonne did not consider niobium foil activation data. Also, the analysis at Argonne originally employed a higher value (304 mb) for the Ni-58(n,p)Co-58g+m reference cross section at 14.7 MeV, based on ENDF/B-VI [ENDF90]. Although this cross section differs by only 4.1% from the 292 mb value accepted for present purposes, its use would noticeably affect the observed consistency in neutron fluence determinations, as established by the analysis at JAERI. Since it is evident that the cross sections from ENDF/B-VI are not so well substantiated in the 14-MeV region, because of an obvious scatter in the available data, there is no reason to prefer the ENDF/B-VI result over the JAERI experimental value at 14.7 MeV. There have been no changes in the assumed Ni-58(n,p)Co-58g+m reference cross sections for 10.3 MeV and for the Be(d,n) spectrum, relative to those results reported in the second Argonne report [Mea+91].

2. EXPERIMENTAL RESULTS

The experimental cross sections obtained from this collaborative experiment are presented in Tables 5 and 6. Total errors associated with these cross sections are also provided in these tables. The results in Table 5 are based entirely on the activity measurements and analysis carried out at Argonne while the values reported in Table 6 are derived from the investigations carried out at both JAERI and Argonne. A review of the analysis carried out at Argonne offered no compelling reasons for altering most of the estimated error components first reported in the second Argonne report [Mea+91], in spite of the obvious differences between the cross section values given earlier and those provided here. The relevant error components for the Argonne results are listed in Tables 7-9. Table 10 gives information on experimental errors for the results derived at JAERI.

3. COMPARISONS OF EXPERIMENTAL DATA WITH CALCULATED RESULTS

Figs. 1 -6 show comparisons of the experimental differential cross-section results at 10.3 and 14.7 MeV from this work (see Tables 5 and 6) with corresponding available calculated values. One set of calculated values was produced by one of the authors (JWM) using the code GNASH [Art88,YA90], and "default" parameters. These calculated results were found to be very sensitive to the details of the assumed level structures. For the most part, this information was derived from Ref. LS78. Three other sets of calculated cross-section values are also included in this report. The values from Chadwick [Cha93] were generated using code GNASH. Default parameters were used, but details on the assumed levels were not available. The results from Yamamuro [Yam93] were also based on a code package built around GNASH. No details were available on the assumed parameters. Finally, some results from Grudzevich [Gru93] were included. No information on these calculations was available either, other than the fact that the code STAPRE was employed.

A comparison was also made between measured (E) and calculated (C) integral results for several reactions. An experimental integral result for the Be(d,n) spectrum is of little worth unless it is compared with what can be calculated from a knowledge of the Be(d,n) spectrum ϕ and the reaction differential cross section σ, using the formula $\langle\sigma\rangle = \int\sigma(E)\phi(E)dE$. The Be(d,n) spectrum representation derived from the experimental work of Meadows [Mea91] was employed for this purpose. Differential cross sections were obtained either from ENDF/B-VI or were computed by one of the authors (JWM) using the nuclear-model code GNASH. The results of these integral/differential comparisons appear in Table 11.

4. DISCUSSION

With the exception of Hf-176(n,2n)Hf-175, where a modest discrepancy remains to be resolved, good agreement (within errors) is observed between the 14.7-MeV results derived from the work at JAERI and Argonne, using distinct samples, activity measurements and analysis techniques, in a common irradiation environment. This suggests that there are no serious systematic errors in the experimental or data analysis procedures, and that the error estimates are reasonable.

The calculated cross section curves generally agree within a factor of two wherever comparisons can be made (see Figs. 1 - 6). The agreement between the calculated and measured cross sections in the vicinity of 14 MeV are reasonably good, but at 10.3 MeV the comparisons are far less favorable. Since the agreement between the experimental results reported in Table 5 for the (n,p) and (n,α) results and ENDF/B-VI [ENDF90] is quite reasonable, we tend to believe that our results for the (n,2n) reactions are acceptable. Therefore, the problem can probably be traced to inadequate knowledge of the level parameters in carrying out the model calculations. These calculations are very sensitive to such details, and to channel competition, in the threshold region. Generally, the calculated results are considerably larger than the corresponding experimental values.

The integral/differential comparisons shown in Table 11 reflect the significant uncertainties in the model calculated cross sections, and in the neutron spectrum itself, in the region of major response to the Be(d,n) neutron spectrum.

Taken together, these results provide a good basis for estimating the activities which might be generated in a fusion reactor by the reactions considered in this investigation.

5. FUTURE WORK

The following tasks remain to be completed in this project:

1. Resolve the discrepancy between ANL and JAERI for the 14.7-MeV cross section of Hf-176(n,2n)Hf-175.

2. Provide recommended experimental 14.7-MeV values based on averaging the results from the work at Argonne and JAERI.

3. Compile other relevant experimental cross-section results from the literature for comparison with the present values.

4. Prepare a detailed formal report on this work for journal publication.

It is planned to complete this project, as defined here, within about a year. It should be pointed out, however, that further counts of the samples retained in Japan may be carried out in the future, when the interfering shorter-lived activities will have died away to a manageable level. As a consequence, additional cross section results could be forthcoming at a later time.

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Table 1: Properties of sample materials in the irradiation packets

Element	Chemical Form	Mass (gram)[a]	Nominal Sample Dimensions (cm)[b]
Ti	Element (metal)	0.546-0.576	2.540 dia x 0.0254 thick
Fe	Element (metal)	1.910-2.032	2.540 dia x 0.0508 thick
Ni	Element (metal)	1.132-1.147	2.540 dia x 0.0254 thick
Cu	Element (metal)	1.163-1.174	2.540 dia x 0.0254 thick
Nb	Element (metal)	0.200-0.300	2.000 dia x 0.0100 thick
Ag	Element (metal)	2.715-2.742	2.540 dia x 0.0508 thick
Eu	Oxide (powder)	1.057-1.223	2.060 dia x 0.318 thick[c]
Tb	Oxide (powder)	1.864-2.498	2.060 dia x 0.318 thick[c]
Hf	Oxide (powder)	2.879-3.184	2.060 dia x 0.318 thick[c]

[a] Range of masses encountered for individual samples of this type.
[b] Exact dimensions vary somewhat from sample to sample.
[c] 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.

Table 2: Reactions considered in the present work

Reaction	Target Isotopic Abundance (%)[a]	Q-value (MeV)[a]
Ti-46(n,p)Sc-46g+m[b]	8.0±0.1	-1.584,-1.728[c]
Fe-54(n,p)Mn-54[d]	5.9±0.2	0.085
Fe-54(n,α)Cr-51[d]	5.9±0.2	0.844
Ni-58(n,p)Co-58g+m[e]	68.077±0.005	0.402,0.377[c]
Ni-60(n,p)Co-60g+m[f]	26.223±0.005	-2.042,-2.101[c]
Cu-63(n,α)Co-60g+m	69.17±0.02	1.715,1.656[c]
Nb-93(n,2n)Nb-92m	100	-8.966
Ag-107(n,2n)Ag-106m	51.839±0.005	-9.627
Ag-109(n,2n)Ag-108m	48.161±0.005	-9.296
Eu-151(n,2n)Eu-150g	47.8±0.5	-7.934
Tb-159(n,2n)Tb-158g+m	100	-8.133,-8.243[c]
Hf-176(n,2n)Hf-175[d]	5.206±0.004	-8.165
Hf-179(n,2n)Hf-178m2	13.629±0.005%	-8.546
Hf-180(n,2n)Hf-179m2	35.100±0.006	-8.493
U-238(n,f)	Enriched deposit[g]	NA[h]

[a] Ref. Tul90.

[b] What is actually measured in the experiment is the production of Sc-46 from neutrons on natural Ti, i.e., the Ti(n,X)Sc-46 reaction. The contribution from Ti-47(n,np)Sc-46 is included. However, the cross section is computed as if all the Sc-46 yield came from Ti-46.

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

[d] There are no isomeric states in the reaction product nucleus.

[e] Primary reference cross section for this experiment.

[f] What is actually measured in the experiment is the production of Co-60g+m from neutrons on natural Ni, i.e., the Ni(n,X)Co-60g+m reaction. The contribution from Ni-61(n,np)Co-60g+m is included. However, the cross section is computed as if all the Co-60g+m yield came from Ni-60.

[g] Calibrated uranium deposit No. U-238-26 [Mea90]. Mass: 950±60 μg. Composition: U-235 (0.415%), U-238(99.585%).

[h] NA: Not applicable.

Table 3: Decay properties of the radioactive nuclei involved in the present investigation

Activity	Jπ	Excitation Energy (MeV)	Half Life[a]	Decay Mode[b]	Measured γ Ray (MeV)	Relevant γ Branch (%)
Sc-46g[c]	4+	g.s.	83.810±0.010 d	β-	0.889	99.984±0.001
Sc-46m[c]	1-	0.143	18.75±0.04 s	IT	NA[d]	NA
Cr-51[e,f]	7/2-	g.s.	27.702±0.004 d	EC,(β+)	0.320	10.08±0.23
Mn-54[e,g]	3+	g.s.	312.12±0.10 d	EC,(β+)	0.835	99.976±0.001
Co-58g[h]	2+	g.s.	70.82±0.03 d	EC,β+	0.811	99.448±0.008
Co-58m[h,i]	5+	0.025	9.15±0.10 h	IT	NA	NA
Co-60g[j]	5+	g.s.	5.2714±0.0005 y	β-	1.333	99.982±0.001
Co-60m[i,j]	2+	0.059	10.47±0.04 m	IT,(β-)	NA	NA
Nb-92m[k]	2+	0.136	10.15±0.02 d	EC,β+	0.934	99.07±0.04
Ag-106m[l]	6+	0.090	8.46±0.10 d	EC,(β+)	0.512	87.7±0.5
Ag-108m[m]	6+	0.109	418±15 y[n]	EC,β+,IT	0.434	90.5±0.6
Eu-150g[o]	5-	g.s.	35.8±1.0 y	EC,(β+)	0.334	96±3
Tb-158g[p]	3-	g.s.	180±11 y	EC,β+,β-	0.944	43.9±1.3
Tb-158m[p]	0-	0.110	10.5±0.2 s	IT	NA	NA
Hf-175[e,q]	5/2-	g.s.	70±2 d	EC	0.343	87.0±0.5
Hf-178m2[r]	16+	2.446	31±1 y	IT	0.325	94.11±0.17
Hf-179m2[s]	25/2-	1.106	25.1±0.3 d	IT	0.454	68.6±3.6

[a] s (second), m (minute), h (hour), d (day), y (year).
[b] Decay branches marked by (...) are negligibly weak.
[c] Ref. Alb86
[d] NA: Not applicable.
[e] There are no isomeric states for this nucleus.
[f] Ref. Chu91 [g] Ref. GJJ87 [h] Ref. Pek90
[i] Isomeric activity not measured directly in this investigation. Decay contributes indirectly to the measured ground state activity.
[j] Ref. AEL86 [k] Ref. Bag92 [l] Ref. Fre+88
[m] Ref. Bla91 [n] Ref. SSD92 [o] Ref. Mat86
[p] Ref. Lee89 [q] Ref. Min76 [r] Ref. Bro88a
[s] Ref. Bro88b

Table 4: Comparison of 14.7-MeV neutron fluence determinations based on the Ni-58(n,p)Co-58g+m and Nb-93(n,2n)Nb-92m reference reactions[a]

Sample Material	Neutron Flux ($n/cm^2/sec$) Ni-58(n,p)Co-58g+m	Nb-93(n,2n)Nb-92m	Ratio
Cu	4.68×10^8 (0.906)[b]	4.78×10^8	1.02
Ag	7.08×10^8 (0.923)	7.16×10^8	1.01
Eu	5.00×10^8 (0.907)	4.87×10^8	0.97
Tb	5.86×10^8 (0.913)	5.77×10^8	0.98
Hf	6.70×10^8 (0.915)	6.69×10^8	1.00

[a] Based on the sample packet investigated at JAERI. Reference cross sections assumed at 14.7 MeV are [Ike+88]: Ni-58(n,p)Co-58g+m, 292 ± 7 mb; Nb-93(n,2n)Nb-92m, 459 ± 11 mb.

[b] Correction factors to the reaction rates of Ni-58(n,p)Co-58g+m for low-energy (degraded) neutrons are shown as (...). They are calculated as the ratio of the reaction rate for neutrons above 11 MeV to the total reaction rates. These values are determined using neutron spectra calculated using the DOT3.5 [RM73] and MORSE-DD [NM84] codes, with a model of the sample geometry. These calculations also utilized neutron-reaction cross section values from JENDL-3 [Shi+90]. An error of 3% is assumed for these calculated factors.

Table 5: Experimental cross sections obtained from this investigation for the Be(d,n)-spectrum and 10.3-MeV neutrons

Reaction	Cross Section (millibarn)[a] Be(d,n)[b]	10.3 MeV[c]
Ti-46(n,p)Sc-46g+m	36.1 (± 2.2%)	244 (± 5.2%)
Fe-54(n,p)Mn-54	177 (± 2.4%)	464 (± 3.1%)
Fe-54(n,α)Cr-51	3.49 (± 2.9%)	42.7 (± 4.9%)
Cu-63(n,α)Co-60g+m	1.92 (± 2.2%)	30.3 (± 4.7%)
Ag-107(n,2n)Ag-106m	0.99 (± 4.9%)	13.3 (± 4.4%)
Ag-109(n,2n)Ag-108m	NA[d]	38.5 (± 10.6%)
Eu-151(n,2n)Eu-150g	14.4 (± 5.8%)	215 (± 7.9%)
Tb-159(n,2n)Tb-158g+m	25.9 (± 9.6%)	575 (± 9.8%)
Hf-176(n,2n)Hf-175	37.2 (± 5.0%)	532 (± 7.2%)
Hf-180(n,2n)Hf-179m2	2.40 (± 7.7%)	11.9 (± 8.5%)
U-238(n,f)	NA	1119 (± 6.5%)[e]

[a] Absolute cross sections are derived from the following reference cross section values for the Ni-58(n,p)Co-58g+m reaction: Be(d,n)-spectrum neutrons, 240 millibarn; 10.3-MeV neutrons, 589 millibarn [ENDF90]. The reference integral cross section is also based on the Be(d,n) spectrum representation from Meadows [Mea91]. The errors are derived from the information provided in Tables 7 and 8. Errors in the applicable standard cross sections are not included.

[b] ANL irradiation. Sample counts and analysis conducted at Argonne.

[c] LANL irradiation. Sample counts and analysis conducted at Argonne.

[d] NA: Not available from the present investigation.

[e] Includes a 6.3% fission-deposit mass error [Mea90] in addition to the error components shown in Table 8.

Table 6: Experimental cross sections obtained from this investigation for 14.7-MeV neutrons

Reaction	Cross Section (millibarn)[a] Argonne[b]	JAERI[c]	Ratio
Ti-46(n,p)Sc-46g+m	306 (± 2.2%)	311 (± 5.6%)	1.02
Fe-54(n,p)Mn-54	283 (± 2.2%)	288 (± 2.7%)	1.02
Fe-54(n,α)Cr-51	85.6 (± 2.5%)	NA[d]	NA
Ni-60(n,p)Co-60g+m	NA	138 (± 2.8%)	NA
Cu-63(n,α)Co-60g+m	41.9 (± 2.2%)	40.2 (± 2.8%)	0.96
Ag-109(n,2n)Ag-108m	694 (± 4.5%)	682 (± 4.7%)	0.98
Eu-151(n,2n)Eu-150g	1257 (± 5.8%)	1258 (± 4.2%)	1.00
Tb-159(n,2n)Tb-158g+m	2037 (± 7.9%)	2072 (± 8.2%)	1.02
Hf-176(n,2n)Hf-175	1772 (± 5.0%)	1986 (± 4.0%)	1.12
Hf-179(n,2n)Hf-178m2	NA	7.2 (± 7.9%)	NA
Hf-180(n,2n)Hf-179m2	22.5 (± 7.1%)	NA	NA

[a] Absolute cross sections are based on an assumption of 292 ± 7 mb for the Ni-58(n,p)Co-58g+m reference cross section at 14.7 MeV [Ike+88]. The errors are derived from Tables 9 and 10. The error in the reference cross section is not included.

[b] JAERI irradiation. Sample counts and analysis conducted at Argonne. Indicated error does not include 4.6% for neutron fluence determination using the Ni-58(n,p)Co-58g+m reference cross section.

[c] JAERI irradiation. Sample counts and analysis conducted at JAERI. Indicated error does not include 4.6% for neutron fluence determination using the Ni-58(n,p)Co-58g+m reference cross section.

[d] NA: Not determined in the present investigation.

Table 7: Error sources for the Be(d,n)-spectrum neutron cross-section determinations

Reaction	γ Yield	Half Life	γ Branch	Activ. Decay	Geom.	Neut. Trans.	Mult. Scat.	(n,γ)[a]	Total Error
	Estimated Error Component (%)								
Ti-46(n,p)	2.1	Neg[b]	Neg	0.1	Neg	0.1	0.6	NA[c]	2.2
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
Cu-63(n,α)	2.2	Neg	Neg	0.1	Neg	0.1	0.3	NA	2.2
Ag-107(n,2n)	2.3	0.1	0.6	4.2	0.1	0.1	0.6	NA	4.9
Eu-151(n,2n)	4.0	2.8	3.1	Neg	0.3	0.1	0.4	NA	5.8
Tb-159(n,2n)	6.8	6.1	3.0	Neg	0.3	0.1	0.4	NA	9.6
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

[a] Uncertainty in the estimated correction for capture activation.
[b] Neg: Negligible (< 0.1%).
[c] NA: Not applicable.

Table 8: Error sources for the 10.3-MeV neutron cross-section determinations

Reaction	γ Yield	Half Life	γ Branch	Activ Decay	Geom	Neut Trans	Mult Scat	(n,γ)[a]	Empty Cell	Total Error
	Estimated Error Component (%)									
Ti-46(n,p)	2.3	Neg[b]	Neg	3.8	0.2	0.1	0.8	NA[c]	2.5	5.2
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
Cu-63(n,α)	2.2	Neg‡	Neg	Neg	0.1	0.1	0.7	NA	4.1	4.7
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	3.6	0.6	0.7	0.1	0.1	0.5	6.0	2.7	10.6
Eu-151(n,2n)	2.8	2.8	3.1	0.7	3.3	0.1	0.8	NA	5.0	7.9
Tb-159(n,2n)	3.1	6.1	3.0	0.7	3.3	0.1	0.3	NA	5.4	9.8
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
U-238(n,f)	NA	NA	NA	NA	Neg	0.1	1.2	Neg	1.2	1.7

[a] Uncertainty in estimated correction for capture activation.
[b] Neg: Negligible (< 0.1%).
[c] NA: Not applicable.

Table 9: Error sources for the 14.7-MeV neutron cross-section determinations at Argonne

Reaction	γ Yield	Half Life	γ Branch	Activ. Decay	Geom.	Neut. Trans.	Mult. Scat.	(n,γ)[a]	Total Error[b]
	Estimated Error Component (%)								
Ti-46(n,p)	2.1	Neg[c]	Neg	0.3	0.2	0.1	0.7	NA[d]	2.2
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
Cu-63(n,α)	2.2	Neg	Neg	0.2	0.1	0.1	0.4	NA	2.2
Ag-109(n,2n)	2.2	3.6	0.6	0.2	1.3	0.1	0.4	0.5	4.5
Eu-151(n,2n)	2.1	2.8	3.1	0.2	3.4	0.1	0.7	NA	5.8
Tb-159(n,2n)	2.1	6.1	3.0	0.2	3.4	0.1	0.5	NA	7.9
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

[a] Uncertainty in estimated correction for capture activation.
[b] Indicated error does not include 4.6% for neutron fluence determination using the Ni-58(n,p)Co-58g+m reference cross section.
[c] Neg: Negligible (< 0.1%).
[d] NA: Not applicable.

Table 10: Error sources for the 14.7-MeV neutron cross-section determinations at JAERI

Reaction	γ Yield	Half Life	γ Branch	Det. Eff.	Sum Coin.	Isot. Abun.	Low-E_n Neut.	Total Error[a]
	Estimated Error Component (%)							
Ti-46(n,p)	4.2	Neg[b]	Neg	2.0	3.0	1.3	1.0	5.6
Fe-54(n,p)	0.7	Neg	Neg	2.0	NA[c]	1.7	Neg	2.7
Ni-60(n,p)	≤ 0.3	Neg	Neg	2.0	1.0	Neg	1.0	2.8
Cu-63(n,α)	0.5	Neg	Neg	2.0	1.0	Neg	1.0	2.8
Ag-109(n,2n)	0.9	2.9	0.8	2.0	3.0	Neg	Neg	4.7
Eu-151(n,2n)	0.5	2.8	2.0	2.0	1.0	1.0	Neg	4.2
Tb-159(n,2n)	0.4	6.1	5.1	2.0	NA	Neg	Neg	8.2
Hf-176(n,2n)	1.3	2.9	0.6	2.0	NA	0.1	Neg	4.0
Hf-179(n,2n)	5.8	3.2	2.0	2.0	3.0	Neg	Neg	7.9

[a] Indicated error does not include 4.6% for neutron fluence determination using the Ni-58(n,p)Co-58g+m reference cross section.
[b] Neg: Negligible.
[c] NA: Not applicable.

Table 11: Integral/differential comparisons for the Be(d,n) neutron spectrum

Reaction	Integral Cross Section (barn) Experimental (E)	Calculated (C)
Ag-107(n,2n)Ag-106m	0.00099	0.00173
Ag-109(n,2n)Ag-108m	NA[a]	0.00157
Eu-151(n,2n)Eu-150g	0.0144	0.0100
Tb-159(n,2n)Tb-158g+m	0.0259	0.0164
Hf-176(n,2n)Hf-175	0.0372	0.0129
Hf-180(n,2n)Hf-179m2	0.0024	0.0000229

[a] NA: Not available.

Figure 1: Differential cross sections for Ag-107(n,2n)Ag-106m. Data points: ANL (∗). Curves: MEADOWS (J.W. Meadows, this work); CHADWICK (Ref. Cha93).

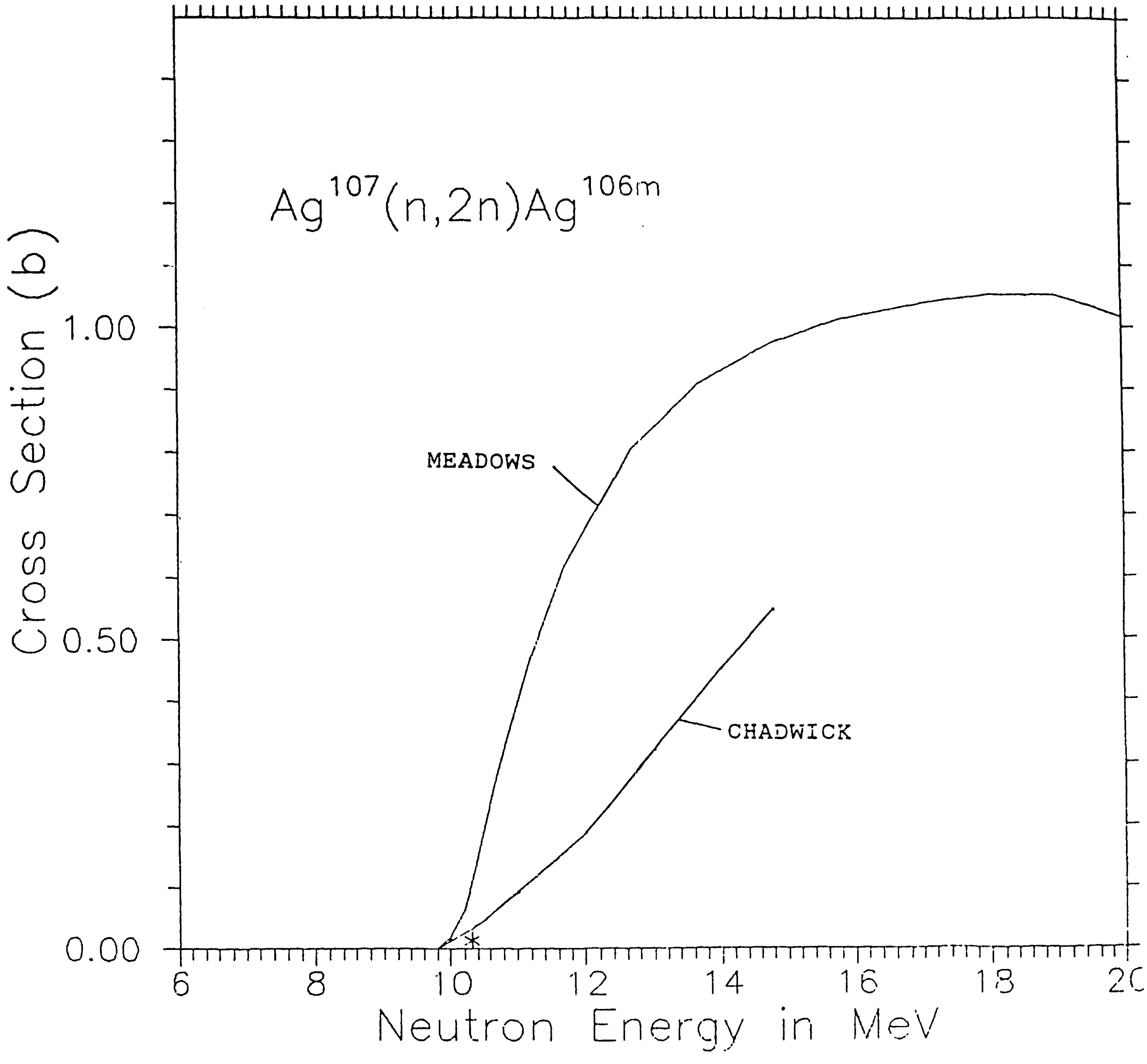


Figure 2: Differential cross sections for Ag-109(n,2n)Ag-108m. Data points: ANL (✳); JAERI (●). Curves: MEADOWS (J.W. Meadows, present work); CHADWICK (Ref. Cha93); YAMAMURO (Ref. Yam93); GRUDZEVICH (Ref. Gru93).

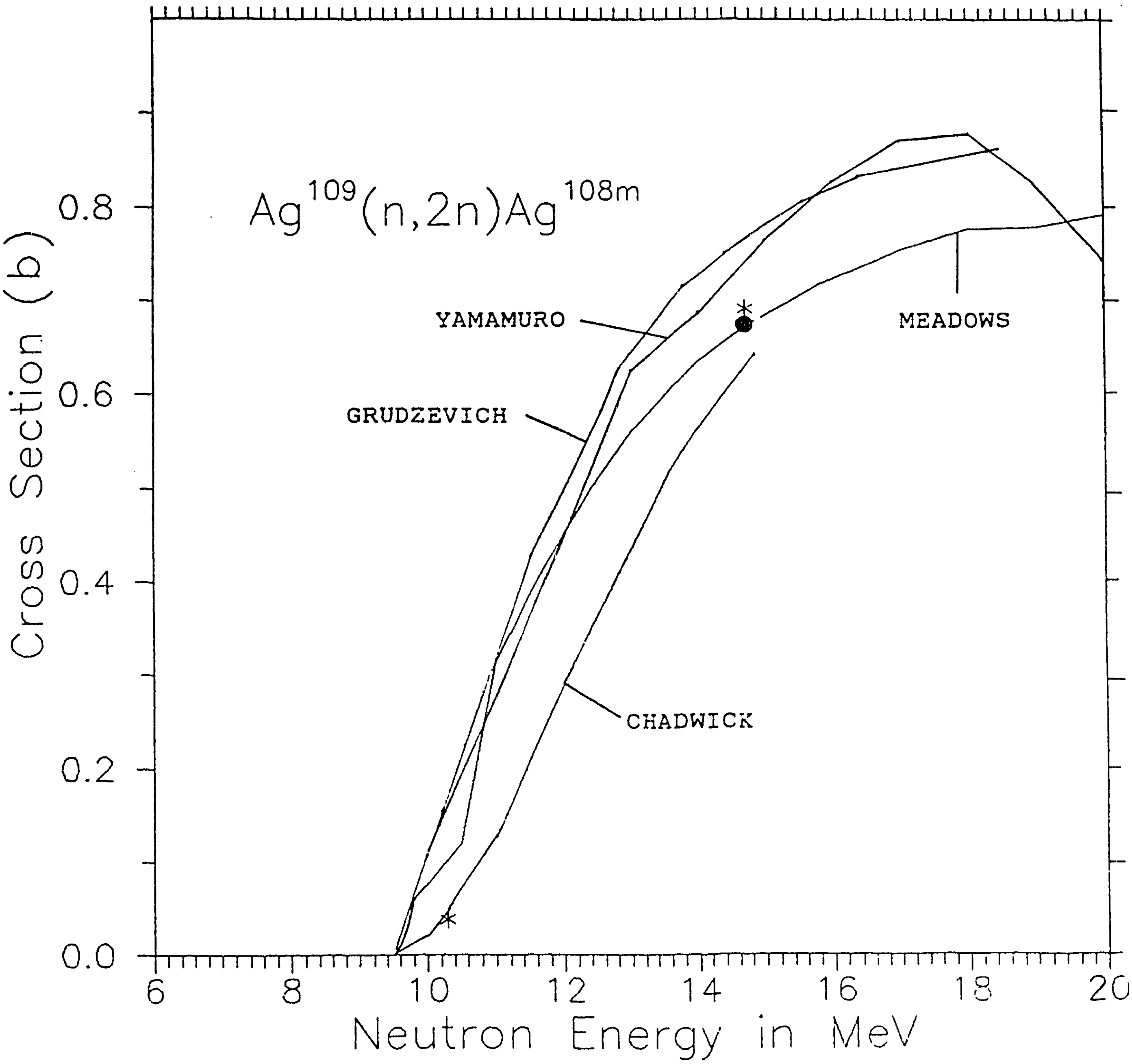
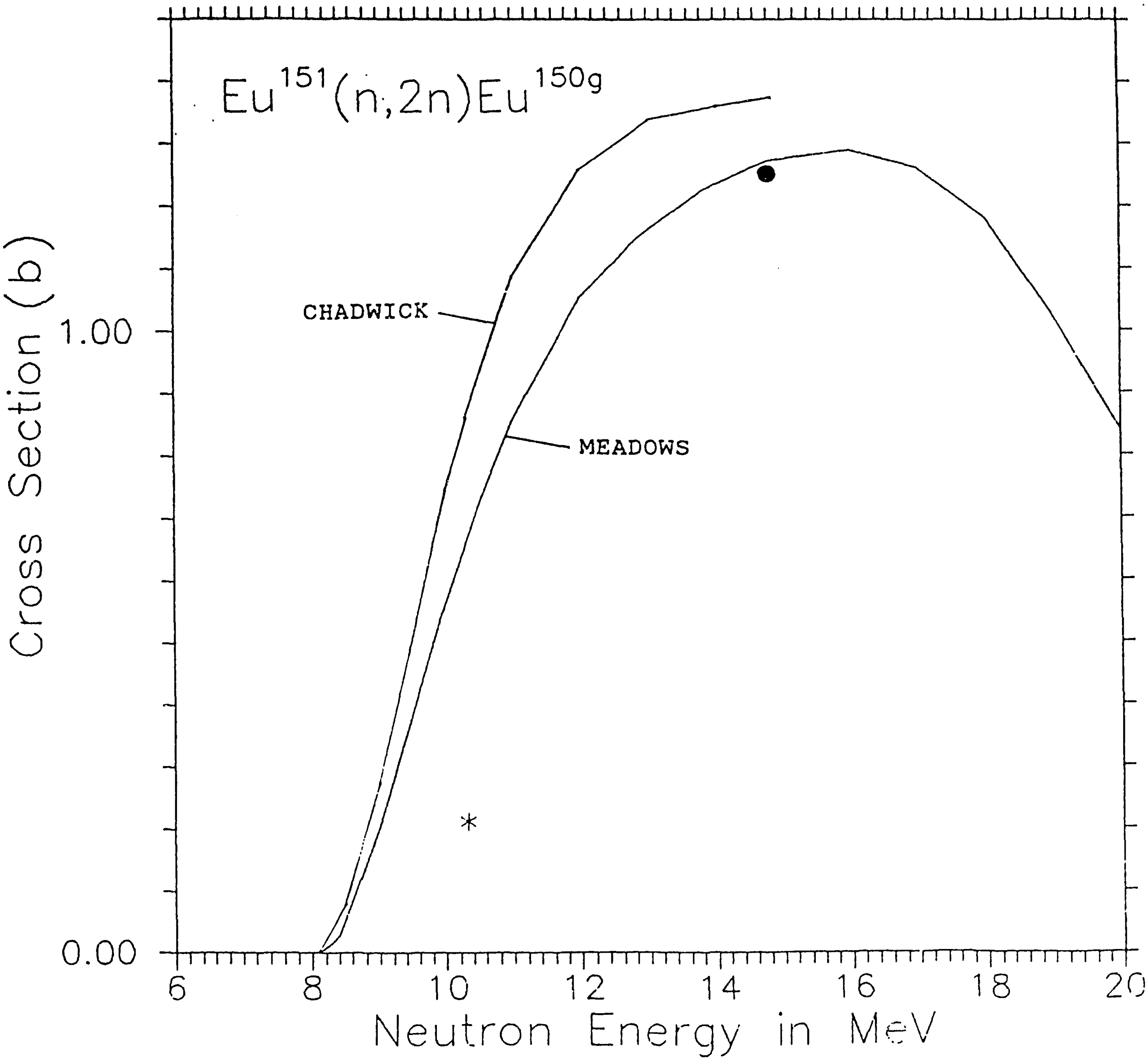


Figure 3: Differential cross sections for Eu-151(n,2n)Eu-150g. Data points: ANL (∗); JAERI (●). Curves: MEADOWS (J.W. Meadows, present work); CHADWICK (Ref. Cha93). Note that ANL and JAERI data points are nearly superimposed at 14.7 MeV.



<u>Figure 4</u>: Differential cross sections for Tb-159(n,2n)Tb-158g+m. Data points: ANL (∗); JAERI (●). Curves: MEADOWS (J.W. Meadows, present work); CHADWICK (Ref. Cha93); GRUDZEVICH (Ref. Gru93).

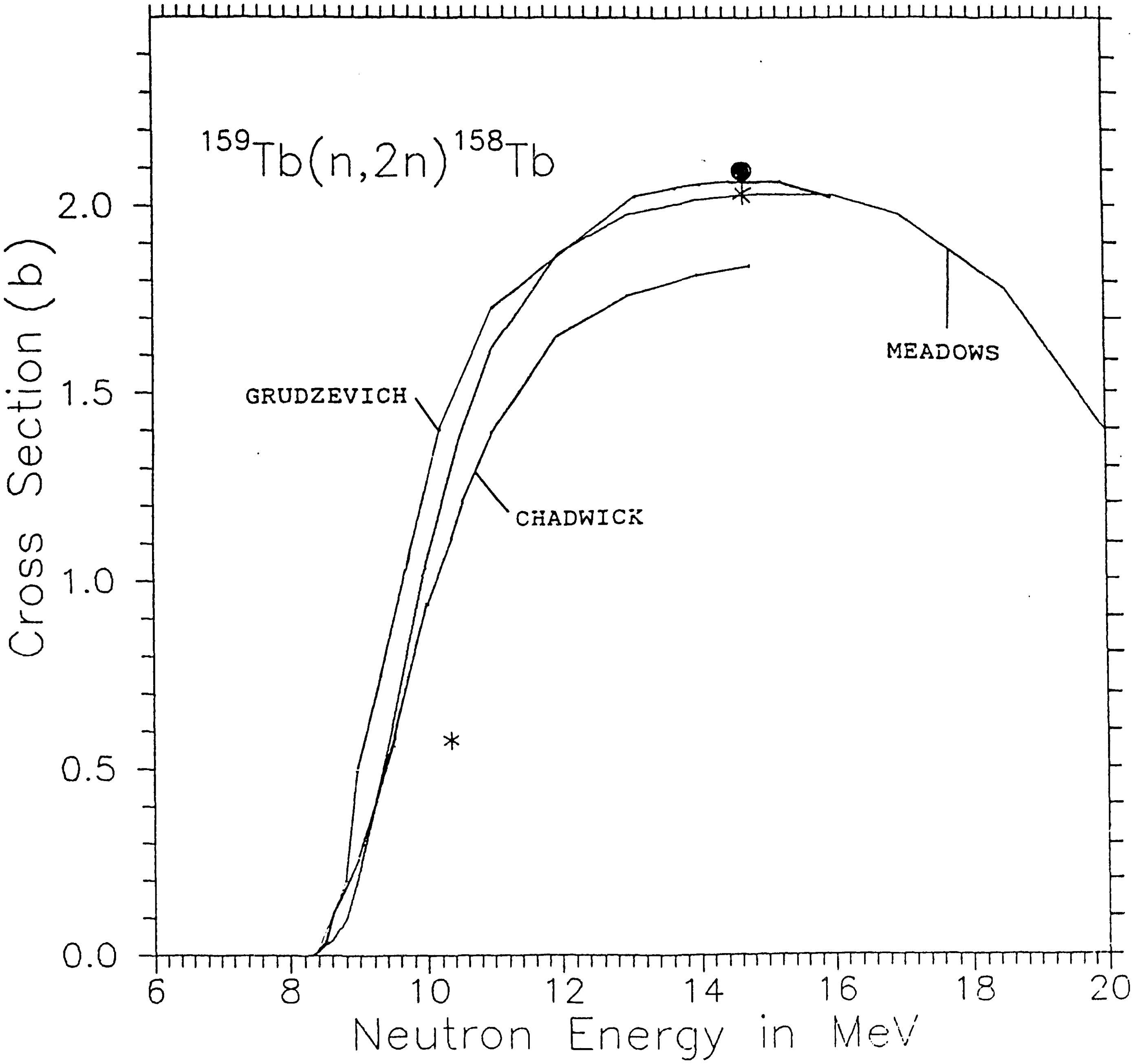


Figure 5: Differential cross sections for Hf-176(n,2n)Hf-175. Data points: ANL (*) JAERI (●). Curves: MEADOWS (J.W. Meadows, present work).

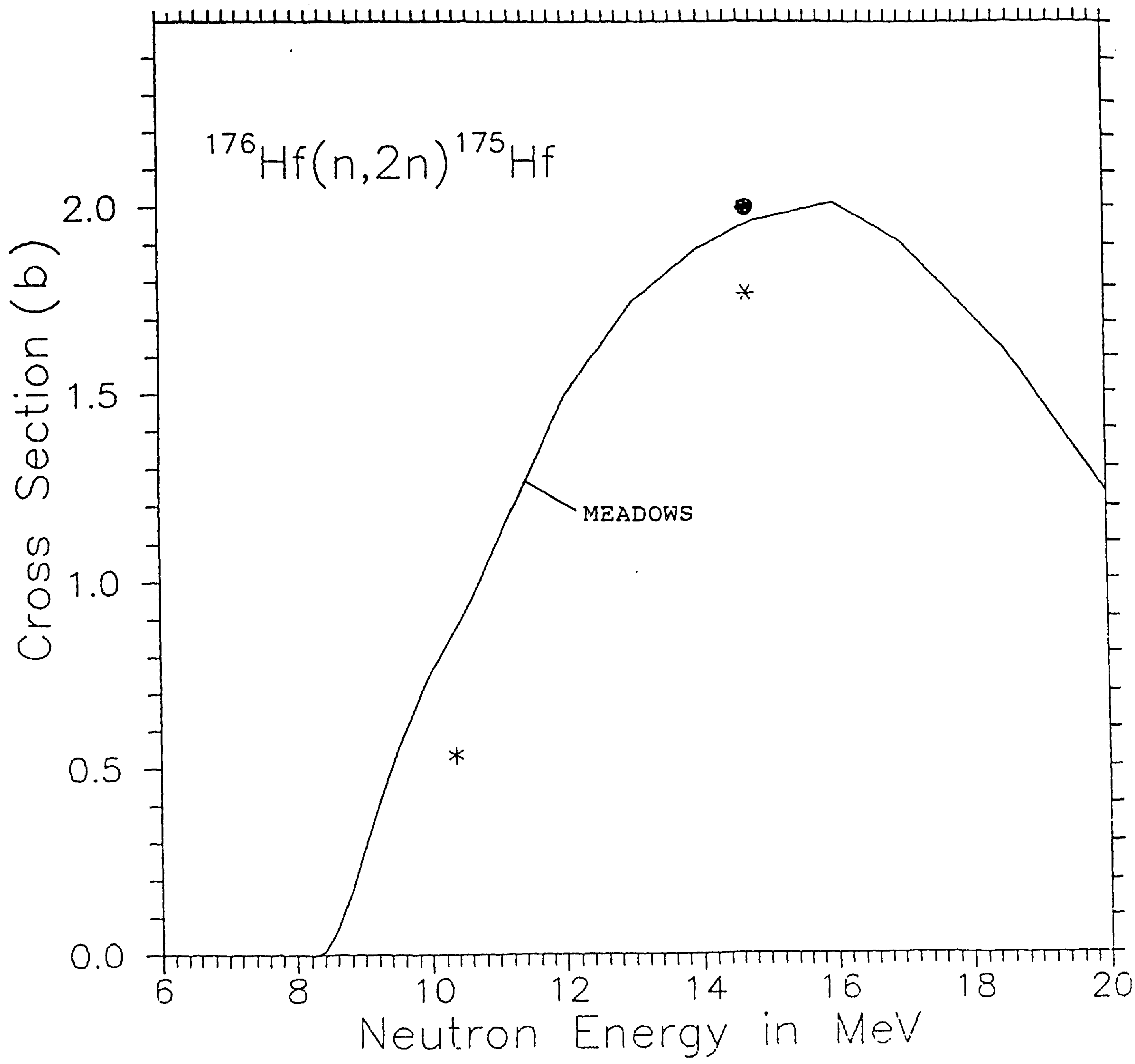
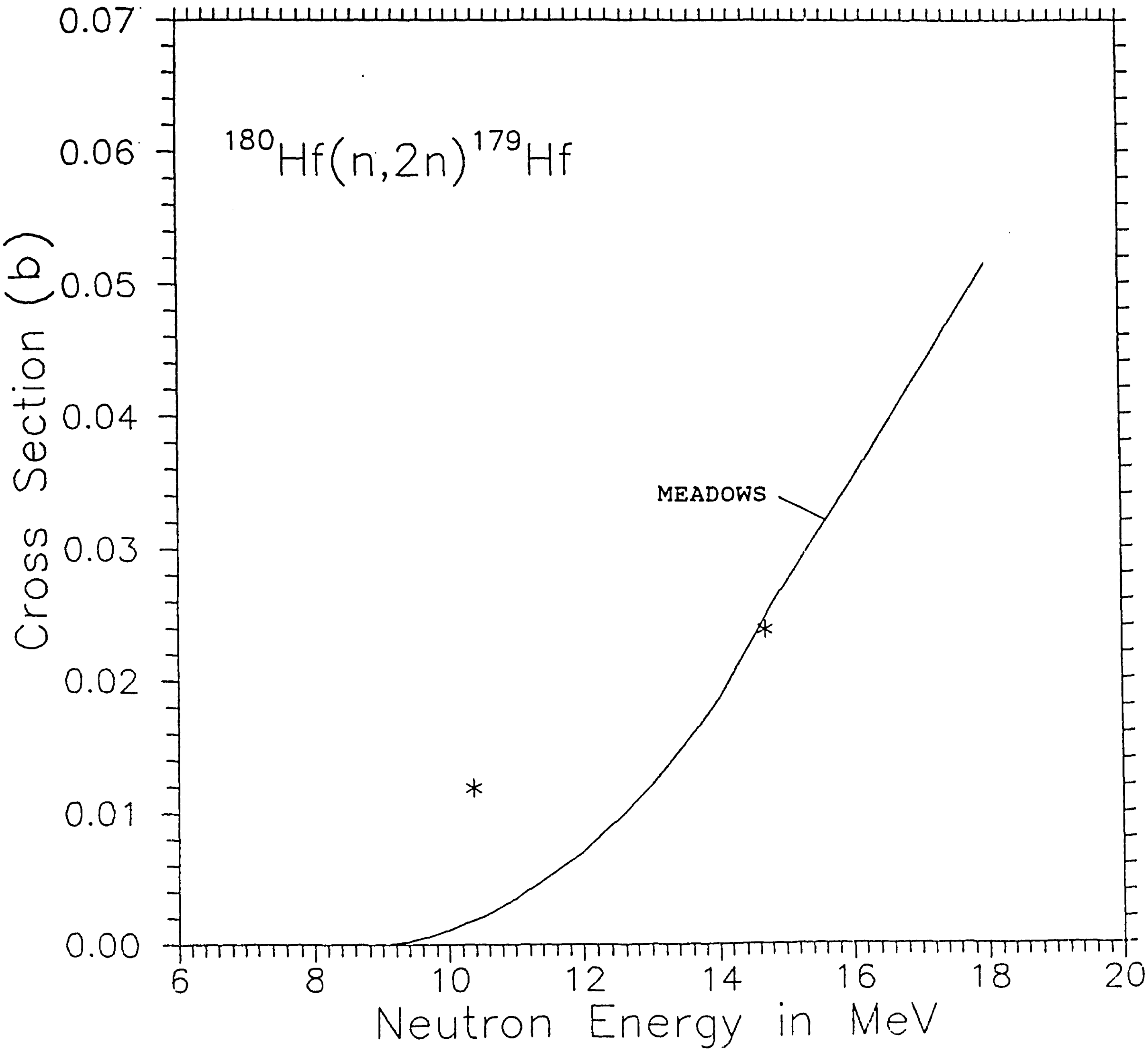


Figure 6: Differential cross sections for Hf-180(n,2n)Hf-179m2. Data points: ANL (*). Curves: MEADOWS (J.W. Meadows, present work).



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