124/5-12-78

Hh. 58

LA-7236-MS

Informal Report

UC-34c

Issued: April 1978

MASTER

An Evaluation of the ^{175}Lu(n,2n)^{174}Lu, ^{175}Lu(n,2n)^{174m}Lu, and ^{175}Lu(n,3n)^{173}Lu Cross Sections from Threshold to 20 MeV

C. Philis*

P. G. Young

E. D. Arthur

*Centre d'Etudes de Bruyères-le-Châtel, B. P. 561 - 92542, Montrouge, CEDEX, FRANCE.

los alamos scientific laboratory

of the University of California

LOS ALAMOS, NEW MEXICO 87545

UNITED STATES

DEPARTMENT OF ENERGY

CONTRACT W-7405-ENG. 36

AN EVALUATION OF THE $^{175}Lu(n,2n)^{174}Lu$, $^{175}Lu(n,2n)^{174m}Lu$, AND $^{175}Lu(n,3n)^{173}Lu$ CROSS SECTIONS FROM THRESHOLD TO 20 MeV

by

C. Philis, P. G. Young, and E. D. Arthur

ABSTRACT

We present an evaluation of the $^{175}Lu(n,2n)^{174}Lu$, $^{175}Lu(n,2n)^{174m}Lu$, and $^{175}Lu(n,3n)^{173}Lu$ reactions from threshold to 20 MeV. Available experimental data were renormalized to a consistent set of standards and were used along with results from statistical-preequilibrium model calculations to produce recommended curves for each of these reactions.

I. INTRODUCTION

We present a preliminary evaluation of the cross sections for the reactions $^{175}Lu(n,2n)^{174}Lu$, $^{175}Lu(n,2n)^{174m}Lu$, and $^{175}Lu(n,3n)^{173}Lu$ that is part of a program intended to improve the knowledge of microscopic nuclear data. In addition, part of this work satisfies Request No. 682036 of WRENDA76.[1]

Here we define the $^{175}Lu(n,2n)^{174m}Lu$ reaction as the one that, either directly or by passing through excited levels with gamma-ray emission, feeds the 142-day half-life, third-excited state of ^{174}Lu. In the same manner, the $^{175}Lu(n,2n)$ and $^{175}Lu(n,3n)$ reactions are those leading respectively to the ground states of ^{174}Lu ($T_{1/2}$ = 3.31 yr) and ^{173}Lu ($T_{1/2}$ = 1.37 yr).

For this evaluation we have analyzed the main publications up to January 1, 1977. As in our previous evaluations,[2-4] wherever possible we have normalized the experimental results to a consistent set of recent standards related to half-lives of the respective radioactive residual nuclei, disintegration schemes and gamma-ray intensities, and cross sections used to determine incident neutron flux.

In the sections that follow we present:

- General information concerning reaction Q values, thresholds, and experimental methods used to obtain cross section of interest,
- Standards used in this evaluation for data normalization,
- Summaries of published experimental results,
- Calculational methods and results,
- Discussion and conclusions.

II. GENERAL INFORMATION

A. Q Values and Thresholds

The Q values and thresholds for the reactions examined here are listed below.[5]

Reaction	Q Value (MeV)	Threshold Energy (MeV)
$^{175}Lu(n,2n)^{174}Lu$	-7.659	7.703
$^{175}Lu(n,2n)^{174m}Lu$	-7.830	7.874
$^{175}Lu(n,3n)^{173}Lu$	-14.447	14.530

B. Experimental Methods

Two methods have been used to obtain experimental values of the cross sections for these reactions:

- Direct measurement of the number of neutrons emitted during the reaction through use of a large liquid scintillator tank, and
- Activation measurements.

Since these two methods have been summarized in previous evaluations[2-4] we shall not describe them here. Note that the first method provides the total (n,2n) or (n,3n) cross sections, while the second case leads to determination of the isomeric and ground state cross sections.

III. STANDARDS USED FOR DATA NORMALIZATION

Each set of selected standards has been chosen from the latest evaluations or compilations.

A. Flux Measurements

- Direct Measurements: For the measurements of Frehaut,[6] fluxes were obtained from the $^{238}U(n,f)$ cross section. For this standard we chose Version IV of the Evaluated Nuclear Data File (ENDF/B-IV),[7] material number (MAT) = 1262.
- Activation Measurements: For these measurements the $^{27}Al(n,\alpha)^{24}Na$ and $^{65}Cu(n,2n)^{64}Cu$ reactions have been used. As standards, we again selected ENDF/B-IV evaluations of these cross sections (MAT = 1193 and 6412, respectively).

B. Decay Schemes

- ^{174m}Lu and ^{174g}Lu. The decay schemes used here are mainly based on data given in Ref. 8. Using the Sliv and Band tables,[9] we have calculated the conversion coefficient factor for the 67.1 keV gamma ray of ^{174}Lu.* The intensities used for normalization, along with major elements of the decay scheme, are shown in Fig. 1.
- ^{173}Lu. The half-life of 1.37 yr was taken from Ref. 10.

*These data are consistent with the values given by Nethaway.[13]

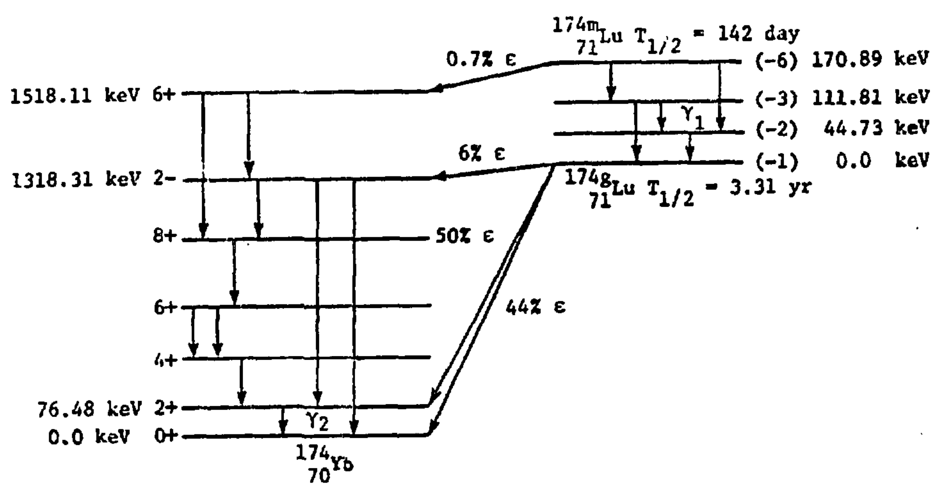

Fig. 1.
Decay scheme of ^{174}Lu. The gamma intensities (number of gamma rays emitted per 100 disintegrations of ^{174m}Lu or ^{174g}Lu) used for the 67.08 (γ_1) and 76.48 keV (γ_2) gamma rays were respectively 7.46 and 5.56%.

IV. MAIN EXPERIMENTAL RESULTS FOR THE $^{175}Lu(n,2n)^{174}Lu$ and $^{175}Lu(n,3n)^{173}Lu$ REACTIONS

For each result, we have summarized the main information extracted and the values obtained after renormalization. For authors who did not indicate half-lives or gamma-ray intensities used, we have used a normalization factor of one. No renormalization led us to increase the error given by the authors.

In order to facilitate normalization, comparison, and discussion, we restrict the (n,2n) results to the total and isomeric (n,2n) reaction cross sections. Thus for ^{175}Lu, the ground state (n,2n) cross section is the difference of the two, if we neglect the intensity of 0.7% leading from ^{174m}Lu to ^{174}Yb nucleus.

SUMMARY NO. 1 (Ref. 11)

AUTHORS: R. G. Wille and R. W. Fink.

REFERENCE: Physical Review 118,1, 242 (1960).

LABORATORY: Dept. of Chemistry, University of Arkansas, Fayetteville, AR (USA).

QUANTITY MEASURED: Cross sections of the reaction $^{175}Lu(n,2n)^{174m}Lu$ at 14.8 MeV.

ACCURACY: $\Delta E_n = \pm 0.8$ MeV, $\Delta\sigma/\sigma = \pm 19\%$.

METHOD OF MEASUREMENT: Activation.

STANDARDS: Cross section $^{65}Cu(n,2n)$: $\sigma = 1020$ mb; $T_{1/2} = 160$ days.

NEUTRON SOURCE: D-T reaction on Zr-T target using deuterons from a Cockcroft-Walton accelerator. Flux: 10^{10} to 10^{11} neutrons/s in 4π.

FLUX MEASUREMENT: $^{65}Cu(n,2n)$ cross section, measurement of the ^{64}Cu activity. Flux monitored with a long counter.

SAMPLES: Metal or oxides pressed in flat tablets with copper monitor foils placed in front and back of the tablets.

CORRECTIONS: Corrections were made for efficiency, air and window transmission, backscattering for aluminum, self-absorption, and background.

ERRORS: No detailed information. Most of the error arises from the uncertainty in estimating the correction factors for absolute counting.

NORMALIZATION - RESULTS: We have renormalized the Wille's value by the $^{65}Cu(n,2n)$ cross section and the half-life of ^{174m}Lu.

E_n (MeV)	$\pm\Delta E_n$ (MeV)	σ_1 (mb)	σ_2 (mb)	σ_3 (mb)	R	σ_4 (mb)	$\Delta\sigma_4/\sigma_4$ (%)
14.8	0.8	1020	984	1600	0.888	1370	19

σ_1 = ^{65}Cu(n,2n) cross section used by Wille.

σ_2 = ^{65}Cu(n,2n) cross section used as the reference standard in this report.

σ_3 = ^{175}Lu(n,2n)^{174m}Lu cross section given by Wille.

R = ratio taking into account the different half-lives for ^{174m}Lu

$$\left[R = \frac{T_{1/2}(\text{standard})}{T_{1/2}(\text{Wille})}\right]$$

σ_4 = ^{175}Lu(n,2n)^{174m}Lu cross section adopted with $\sigma_4 = R \cdot \sigma_3(\sigma_2/\sigma_1)$.

SUMMARY NO. 2 (Ref. 12)

AUTHORS: W. Dilg, H. Vonach, G. Winkler, and P. Hille

REFERENCE: Nuclear Physics A118, 9 (1968).

LABORATORY: Physik department der Technischen Hochschule, Munchen (Germany).

QUANTITY MEASURED: $^{175}Lu(n,2n)^{174g+m}Lu$ cross sections for 14.7 MeV.

ACCURACY: $\Delta E_n = \pm$ 0.15 MeV; $\Delta\sigma/\sigma = \pm$ 10.9% for $^{175}Lu(n,2n)^{174g}Lu$ and
$\Delta\sigma/\sigma = \pm$ 8.4% for $^{175}Lu(n,2n)^{174m}Lu$.

METHOD OF MEASUREMENT: Activation.

STANDARDS: Cross section $^{27}Al(n,\alpha)^{24}Na$: σ = 111.5 mb $\pm$ 1.5%.

NEUTRON SOURCE: $T(d,n)^4He$ with 400 keV deuterons from a Van de Graaff.

MEASUREMENT OF THE FLUX: Measurement of the activity of ^{24}Na produced by the $^{27}Al(n,\alpha)^{24}Na$ reaction.

SAMPLES: Lu oxide, 25 mm diameter, placed between two aluminum disks.

CORRECTIONS: Self-absorption.

ERRORS: Three times the mean statistical error added to the largest systematic error.

NORMALIZATION- RESULTS: *The values of Dilg have been renormalized by the* $^{27}Al(n,\alpha)^{24}Na$ cross sections.

E_n (MeV)	$\pm E_n$ (MeV)	σ_1 (mb)	σ_2 (mb)	σ_3 (mb)	σ_4 (mb)	σ_5 (mb)	σ_6 (mb)	σ_7 (mb)	$\pm\Delta\sigma/\sigma$ (%)
14.7	*0.15*	*111.5*	*116.8*	*655*		*1285*		*2032*	
					686.1				8.3
							1346		10.9

σ_1 = $^{27}Al(n,\alpha)^{24}Na$ cross section used by Dilg.

σ_2 = $^{27}Al(n,\alpha)^{24}Na$ cross section used as the standard in this report.
σ_3 = $^{175}Lu(n,2n)^{174m}Lu$ cross section given by Dilg.
σ_4 = $^{175}Lu(n,2n)^{174m}Lu$ cross section adopted with $\sigma_4 = \sigma_3 \cdot \sigma_2/\sigma_1$.
σ_5 = $^{175}Lu(n,2n)^{174g}Lu$ cross section given by Dilg.
σ_6 = $^{175}Lu(n,2n)^{174g}Lu$ cross section adopted with $\sigma_6 = \sigma_5\sigma_2/\sigma_1$.
σ_7 = $^{175}Lu(n,2n$ cross section adopted $\sigma_7 = \sigma_6 + \sigma_4$.

SUMMARY NO. 3 (Ref. 13)

AUTHOR: D. R. Nethaway

REFERENCES: Nuclear Physics A190, 635 (1972) and private communication 1975.

LABORATORY: Lawrence Livermore Laboratory, Livermore CA (USA).

QUANTITY MEASURED: Cross section $^{175}Lu(n,2n)^{174}Lu$ for 8 energies from 13.8 to 14.4 MeV.

METHOD OF MEASUREMENT: Activation.

ACCURACY: $\Delta E_n = \pm 0.025$ MeV; $\Delta\sigma/\sigma = \pm 10.2\%$.

STANDARDS: $^{27}Al(n,\alpha)^{24}Na$ $\sigma = 117.0 \pm 0.8$ mb at 14.43 ± 0.015 MeV (Ref. 14). $T_{1/2}$ (^{174m}Lu) = 142 days; $T_{1/2}$ (^{174g}Lu) = 1204 days, I_γ (76.5 keV) = 0.059* I_γ (67.1 keV) = 0.074.**

NEUTRON SOURCE: D-T reaction on rotating target with insulated core transformed flux : 1-2 x 10^{12} n/s

SAMPLES: Disks of Lu_2O_3, 0.5 in. diameter, 0.25 mm thick, pressed in plastic.

MEASUREMENT OF THE FLUX: $^{27}Al(n,\alpha)^{24}Na$ cross section [measured the activity of ^{24}Na with Ge(Li)]. A curve of the neutron fluence vs energy was determined. Neutron flux density monitored with a proton telescope counter.

EXPERIMENTAL SETUP: Aluminum monitor foils were interspersed among the target foils and taped to the outside of the surface of a hollow aluminum sphere at various angles.

CORRECTIONS: Self-absorption in the sample, small variations in neutron yields.

ERRORS: The error given does not take into account the uncertainty due to decay scheme with which the final result is strongly correlated.

NORMALIZATION - RESULTS: We have renormalized the Nethaway values taking into account gamma-ray intensities and using the recommended $^{27}Al(n,\alpha)$ cross section as well as the given fluence curve. The constant value of 1760 ± 180 mb has been taken from 14.1 to 14.8 MeV as the average given by Nethaway. The ratio $\sigma[^{175}Lu(n,2n)^{174m}Lu]/\sigma[^{175}Lu(n,2n)^{174g}Lu]$ has been taken equal to 0.47.

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*For one disintegration of ^{174g}Lu.

**For one disintegration of ^{174m}Lu.

E_n (MeV)	$\pm\Delta E_n$ (MeV)	σ_1 (mb)	σ_2 (mb)	σ_3 (mb)	R_1	σ_4 (mb)	σ_5 (mb)	R_2	σ_6 (mb)	σ_7 (mb)	$\pm\Delta\sigma/\sigma$ (%)
14.10	0.025	120.4	123.6	563	0.987	570.4	1197	1.054	1295.2	1865.6	10
14.80	0.025	111.1	115.5	563	0.987	577.7	1197	1.054	1311.60	1889.3	10

R_1 = Normalization factor taking into account the intensities of the 67.1 gamma ray (R_1 = 0.074/0.075).

R_2 = Normalization factor taking into account the intensities of the 76.5 gamma ray (R_2 = 0.059/0.056).

σ_1 = $^{27}Al(n,\alpha)^{24}Na$ cross section used by Nethaway.

σ_2 = $^{27}Al(n,\alpha)^{24}Na$ cross sections used as reference standard in this report.

σ_3 = $^{175}Lu(n,2n)^{174m}Lu$ cross section given by Nethaway with σ_m/σ_g = 0.47.

σ_5 = $^{175}Lu(n,2n)^{174g}Lu$ cross section given by Nethaway.

σ_4 = $^{175}Lu(n,2n)^{174m}Lu$ cross section: adopted values with $\sigma_4 = R_1\sigma_3(\sigma_2/\sigma_1)$.

σ_6 = $^{175}Lu(n,2n)^{174g}Lu$ cross section: adopted values with $\sigma_6 = R_2\sigma_5(\sigma_2/\sigma_1)$.

σ_7 = $^{175}Lu(n,2n)^{174}Lu$ cross section: adopted values with $\sigma_7 = \sigma_4 + \sigma_6$.

SUMMARY NO. 4 (Ref. 6)

AUTHORS: J. Frehaut and G. Mosinski.

REFERENCE: CEA-R-4627 (1974) and "Nuclear Cross Sections and Technology, Proceedings of a Conference," National Bureau of Standards (NBS) Special Publication 425 (1975), p. 855.

LABORATORY: Centre d'Etudes de Bruyères-le-Châtel (France).

QUANTITY MEASURED: $^{175}Lu(n,2n)^{174}Lu$ for 14 energies from 8.44 to 14.76 MeV.

METHOD OF MEASUREMENTS: Direct measurement.

ACCURACY: ΔE_n: from $\pm$ 65 to $\pm$ 140 keV; $\Delta\sigma/\sigma$: from $\pm$ 5.1 to $\pm$ 9.0%.

STANDARDS: $^{238}U(n,f)$ cross section.

NEUTRON SOURCE: D-T reaction with gaseous target on a tandem Van de Graaff.

SAMPLES: Powder of Lu oxide (15 g) wrapped in a thin polyethylene foil.

MEASUREMENTS: Alternately made with monitor and sample. Flux was controlled by a small liquid scintillator counter.

EXPERIMENTAL SETUP: Sample and monitor placed alternatively in the center of a spherical liquid scintillator tank that permitted multiplicities of the number of neutrons emitted to be counted.

CORRECTIONS: Background, multiple events pile-up, events due to the container of the sample, break-up neutrons, and dead time.

ERRORS: Statistical errors combined quadratically. Does not include $^{238}U(n,f)$ cross-section error.

NORMALIZATION - RESULTS: We have normalized Frehaut's values by the values of the $^{238}U(n,f)$ cross section used as standard.

E_n (MeV)	$\pm E_n$ (MeV)	σ_1 (mb)	σ_2 (mb)	σ_3 (mb)	σ_4 (mb)	$\Delta\sigma_4/\sigma_4$ (%)
8.44	0.140	962	999	180	187	21
8.94	0.125	964	993	686	707	7.2
9.44	0.120	960	983	1220	1249	9.0
9.93	0.110	952	975	1482	1518	5.6
10.42	0.100	948	977	1709	1761	5.6
10.91	0.095	952	982	1872	1931	6.7
11.40	0.090	957	986	1802	1857	5.8
11.88	0.085	965	993	1878	1932	5.5
12.36	0.085	978	1012	2060	2132	5.8
12.85	0.080	999	1039	2101	2185	5.9
13.33	0.075	1031	1081	2134	2237	5.1
13.80	0.075	1086	1123	2195	2270	5.2
14.28	0.070	1163	1179	2071	2099	7.3
14.76	0.065	1226	1236	2252	2270	7.2

σ_1 = $^{238}U(n,f)$ cross sections used by Frehaut as standard.

σ_2 = $^{238}U(n,f)$ cross sections used as reference standard in this report.

σ_3 = $^{175}Lu(n,2n)^{174}Lu$ cross sections given by Frehaut.

σ_4 = $^{175}Lu(n,2n)^{174}Lu$ cross sections adopted with $\sigma_4 = \sigma_3(\sigma_2/\sigma_1)$.

SUMMARY NO. 5 (Ref. 15)

AUTHOR: S. M. Qaim.

REFERENCES: Nuclear Physics A224, 319 (1974) and private communication (1974).

LABORATORY: Institut fur Nuklearchemie der Kernforschungsanlage Jülich GmbH. (Germany).

QUANTITIES MEASURED: $^{175}Lu(n,2n)^{174m}Lu$ and $^{175}Lu(n,2n)^{174g}Lu$ at 14.7 MeV.

ACCURACY: $\Delta E_n = \pm 0.3$ MeV; $\Delta\sigma/\sigma = \pm 8.3$ and $\pm 11.4\%$.

METHOD OF MEASUREMENT: Activation.

STANDARDS: $^{27}Al(n,\alpha)^{24}Na$: $\sigma = 121 \pm 6$ mb; $^{75}As(n,2n)^{74}As$: $\sigma = 970 \pm 80$ mb at 14.7 MeV; $T_{1/2}$ (^{174m}Lu) = 142 days; $T_{1/2}$ (^{174g}Lu) = 3.3 yr; I (67 keV transition) = 1.0; I (76.5 keV transition) = 0.62.

NEUTRON SOURCE: $^{3}H(d,n)^{4}He$ reaction on a Dynagen neutron generator.

SAMPLES: Powder mixture of 0.2-1 g of lutetium (>99.9%) with 0.05 g of monitor substance packed in a thin polyethylene foil.

FLUX MEASUREMENTS: Measured ^{24}Na or ^{74}As formed during irradiation.

EXPERIMENTAL SETUP: Samples placed behind the target (^{3}H) in order to get high fluxes (7-9 x 10^{9} $cm^{-2}s^{-1}$).

CORRECTIONS: Geometry, absorption, and internal conversion.

ERRORS: Random error obtained by weighting mean error. In addition, systematic errors (neutron fluxes, photopeak efficiency) were taken into account.

NORMALIZATION - RESULTS: Qaim did not indicate if the standard cross section used was $^{27}Al(n,\alpha)$ or $^{75}As(n,2n)$. However, it was stated that the results obtained by these two reactions were consistent. Therefore we have taken $^{27}Al(n,\alpha)$ as the standard, and have normalized for the intensities of the transition.

E_n (MeV)	$\pm\Delta E_n$ (MeV)	σ_1 (mb)	σ_2 (mb)	σ_3 (mb)	σ_4 (mb)	R_1	R_2	σ_5 (mb)	σ_6 (mb)	σ_7 (mb)	$\pm\Delta\sigma/\sigma$ (%)
14.7	0.30	121	116.8	627		1.029		623			2.3
					1276		1.061		1307		11.4
										1930	

σ_1 = $^{27}Al(n,\alpha)^{24}Na$ cross section used by Qaim as standard.

σ_2 = $^{27}Al(n,\alpha)^{24}Na$ cross section used as reference standard in this report.

σ_3 = $^{175}Lu(n,2n)^{174m}Lu$ cross section given by Qaim.

σ_4 = $^{175}Lu(n,2n)^{174g}Lu$ cross section given by Qaim.

R_1 = Factor taking into account the normalization of the intensities of gamma rays for ^{174m}Lu.

R_2 = Factor taking into account the normalization of the intensities of gamma rays for ^{174g}Lu.

σ_5 = $^{175}Lu(n,2n)^{174m}Lu$ cross section adopted with $\sigma_5 = R_1 \cdot \sigma_3 \cdot \sigma_2/\sigma_1$.

σ_6 = $^{175}Lu(n,2n)^{174g}Lu$ cross section adopted with $\sigma_6 = R_2 \cdot \sigma_4 \cdot \sigma_2/\sigma_1$.

σ_7 = $^{175}Lu(n,2n)^{174}Lu$ cross section adopted with $\sigma_7 = \sigma_5 + \sigma_6$.

SUMMARY NO. 6 (Ref. 16)

AUTHORS: B. P. Bayhurst, J. S. Gilmore, R. J. Prestwood, J. B. Wilhemy, N. Jarmie, B. H. Erkila, and R. A. Hardekopf.

REFERENCES: Physical Review C12, 451 (1975).

LABORATORY: Los Alamos Scientific Laboratory, Los Alamos, NM (USA).

QUANTITY MEASURED: $^{175}Lu(n,2n)^{174}Lu$ and $^{175}Lu(n,3n)^{173}Lu$ for energies from 8.51 to 28.01 MeV.

ACCURACY: ΔE_n: from $\pm$ 0.05 $\pm$ 0.36 MeV; $\Delta\sigma/\sigma$: 4.6 and 4.3 %.

METHOD OF MEASUREMENT: Activation.

STANDARDS: $^{27}Al(n,\alpha)^{24}Na$, $T_{1/2}$ (^{174m}Lu) = 142 days; $T_{1/2}$ (^{173}Lu) = 512 days; $\sigma_m(n,2n)/\sigma_g(n,2n)$ = 0.475.

NEUTRON SOURCES: From 7.6 to 9.3 MeV, $^{1}H(t,n)^{3}He$; from 13.4 to 22 MeV, $^{2}H(d,n)^{3}He$ and $^{3}H(d,n)^{4}He$; from 22 to 28 MeV, $^{2}H(t,n)^{4}He$. Crockroft-Walton from 13.4 to 14.9 MeV; for other energies, Van de Graaff.

MEASUREMENT OF THE FLUX: Relative measurements while recording both beam intensity and pressure of the target. Proton telescope for E_n > 20 MeV.

SAMPLE: Disks 9.5 mm diameter of lutetium (t = 0.55 mm) and Al (t = 0.13 mm) stacked in a light-weight container.

EXPERIMENTAL SETUP: Container placed at different angles on the Cockroft-Walton. Container placed behind the target with varying energy beams on the Van de Graaff.

CORRECTIONS: Decay of the radioactivity during irradiation, geometry (1%), absorption of neutrons in the front wall of the telescope (1.1%); nuclear reactions in the NaI detector (0.6%), dead time of electronics (1.0%).

ERRORS: Neutron fluence determined by the telescope, 2-3%; standard cross section, 3%.

NORMALIZATION - RESULTS: We have normalized Bayhurst's values by the $^{27}Al(n,\alpha)^{24}Na$ cross section and by the half-lives of ^{174m}Lu and ^{173}Lu.

E_n (MeV)	$\pm\Delta E_n$ (MeV)	σ_1 (mb)	σ_2 (mb)	σ_3 (mb)	σ_4 (mb)	$\pm\Delta\sigma_4/\sigma_4$ (%)	σ_5 (mb)	σ_6 (mb)	$\pm\Delta\sigma_6/\sigma_6$ (%)
8.51	0.34	59.3	56.5	323	308	4.6			
9.27	0.36	77.1	76.7	816	812	4.3			
14.10	0.05	122	123	1789	1804	4.3			
14.92	0.05	107	114	1668	1777	4.3	55	57	55
16.18	0.14	88.8	93.9	1580	1671	4.3	150	155	30
17.19	0.19	74.1	76.3	1337	1377	4.3	673	677	12
18.19	0.13	55.9	61.0	965	1053	4.3.	1070	1141	13
19.94	0.15	39.6	38.7	574	561	4.3	1530	1461	9
21.21	0.21	29.9		303	303	4.3	1740	1700	11
21.94	0.19	25.9		342	342	4.3	1757	1717	6
23.32	0.14	17.8		287	287	4.3	1808	1766	13
24.46	0.15	15.3		246	246	4.3	1855	1812	6
26.03	0.15	9.9		190	190	4.3	1678	1639	10
28.01	0.17	2.6		169	169	4.3	1360	1329	10

σ_1 = $^{27}Al(n,\alpha)^{24}Na$ cross section used by Bayhurst as standard.

σ_2 = $^{27}Al(n,\alpha)^{24}Na$ cross section used as reference standard in this report.

σ_3 = $^{175}Lu(n,2n)^{174}Lu$ cross section given by Bayhurst.

σ_4 = $^{175}Lu(n,2n)^{174}Lu$ cross section adopted with $\sigma_4 = \sigma_3 \times \sigma_2/\sigma_1$.

σ_5 = $^{175}Lu(n,3n)^{173}Lu$ cross section given by Bayhurst.

σ_6 = $^{175}Lu(n,3n)^{173}Lu$ cross section adopted with $\sigma_6 = \sigma_5 \times R \times \sigma_2/\sigma_1$.

R = Ratio taking into account the normalization of the half-life of ^{173}Lu (R = 500.39/512) = 0.977.

SUMMARY NO. 7 (Ref. 17)

AUTHORS: L. R. Veeser, E. D. Arthur, and P. G. Young.

REFERENCE: Proceedings of the International Conference on the Interaction of Neutrons with Nuclei, Lowell MA (USA), p. 1351 (1976), and private communication (1977).

LABORATORY: Los Alamos Scientific Laboratory, Los Alamos, NM (USA).

QUANTITY MEASURED: $^{175}Lu(n,2n)^{174}Lu$ for 10 energies between 14.7 and 24 MeV and $^{175}Lu(n,3n)^{173}Lu$ for 9 energies between 16 and 24 MeV.

METHOD OF MEASUREMENT: Direct.

ACCURACIES: ΔE from $\pm$ 60 to $\pm$ 200 keV; $\Delta\sigma/\sigma$ (n,2n) from 5 to 30%; $\Delta\sigma/\sigma$ (n,3n) from 6 to 18%.

STANDARDS: Absolutely calibrated liquid scintillator monitor using data of Verbinski et al. (Ref. 18).

NEUTRON SOURCE: Tritium gas target, deuterons from a Van de Graaff.

SAMPLES: Two disks (6 cm diameter) of 97.41% ^{175}Lu and 2.59% ^{176}Lu.

MEASUREMENT OF FLUX: Absolute using calibrated scintillator described above.

EXPERIMENTAL SETUP: Sample placed inside a 75-cm-diameter spherical tank in which the neutron multiplicities were counted.

CORRECTIONS: Background, multiple events, detector deficiency due to shape of the emitted neutron spectrum.

ERRORS: Total uncertainty is a combination of the statistical uncertainty, the uncertainty in the correction described above, and an estimated $\pm$ 3% uncertainty in the flux determination.

NORMALIZATION - RESULTS: We have not renormalized these data. The results for (n,2n) and (n,3n) appear on the following page.

E_n (MeV)	ΔE_n (MeV)	σ_1 (mb)	$\Delta\sigma_1$ (mb)	σ_2 (mb)	$\Delta\sigma_2$ (mb)
14.7	0.15	1.984	0.115		
16.0	0.2	1.992	0.105	0.147	0.027
17.0	0.2	1.787	0.085	0.455	0.034
18.0	0.15	1.32	0.088	0.699	0.053
19.0	0.15	0.957	0.064	1.099	0.067
20.0	0.11	0.77	0.104	1.226	0.082
21.0	0.12	0.722	0.068	1.295	0.077
22.0	0.10	0.535	0.079	1.405	0.09
23.0	0.07	0.562	0.098	1.421	0.096
24.0	0.06	0.524	0.154	1.572	0.1

σ_1 and σ_2 are the measured $^{175}Lu(n,2n)$ and $^{175}Lu(n,3n)$ cross sections.

V. CALCULATIONAL RESULTS

A. Code Description

We have calculated ^{175}Lu(n,2n) and ^{175}Lu(n,3n) reactions from their respective thresholds up to an energy of 24 MeV. To make these calculations, we used the preequilibrium-statistical model code GNASH.[19] The statistical portion of the code includes angular momentum and parity effects explicitly and generally follows the formalism of Uhl.[20] Decay chains involving up to 10 compound nuclei can be followed, with the possibility of the emission of six types of radiation from each decaying compound nucleus. The code allows the calculation of spectra (both particle and gamma ray) as well as reaction cross sections. In addition, level activation and gamma-ray deexcitation cross sections can be obtained for up to 50 discrete levels for each residual nucleus involved in the decay sequences. Gamma-ray cascades are followed in detail, which permits activation cross sections and isomer ratios to be obtained.

Widths for particle decay are computed from transmission coefficients obtained from external optical model routines[21] while gamma-ray widths are presently calculated using either the Weisskopf single-particle approximation[22] or the Brink-Axel giant dipole resonance model.[23] These widths are then normalized to the ratio of the average gamma-ray width $\langle \Gamma_\gamma \rangle$ and the observed level spacing $\langle D \rangle$ obtained from s-wave neutron capture. Preequilibrium corrections to cross sections, level populations, and spectra are made with a simplified preequilibrium form based on the exciton model.[24] Since this preequilibrium model does not include effects of spin and parity, we have assumed that the preequilibrium component has the same spin and parity distribution as the statistical component. To describe the continuum excitation energy region in each residual nucleus, for which no discrete level information is available, we have used the Gilbert-Cameron level density expression.[25] Here a Fermi-gas expression is used at high-excitation energies, while a constant-temperature expression, adjusted to fit inputted level parameters for each nucleus, is used at lower excitation energies.

B. Assumption and Results of ^{175}Lu(n,2n) and ^{175}Lu(n,3n) Calculations

The optical model transmission coefficients were calculated using the external optical model code TCCOMP.[26] Table I lists the neutron optical model parameters that result from the global parameter set of Wilmore and Hodgson.[27] Although the Wilmore-Hodgson parameters were generally obtained from fits to

TABLE I

NEUTRON OPTICAL MODEL PARAMETERS
FOR Lu CALCULATIONS

Parameter	Value Used
V (MeV)	$47.01 - 0.267E - 0.0018E^2$
r_0 (f)	1.269
a (f)	0.66
W_D (MeV)	$9.52 - 0.053E$
r_D (f)	1.241
a_D (f)	0.48
V_{SO} (MeV)	7.0

experimental data involving spherical nuclei, they still give reasonable results for the case of Lu, which is deformed. In this calculation only neutron and gamma-ray emission were allowed from each compound nucleus because the competition from charged-particle emission is small. Thus, (n,p), (n,α), (n,np), (n,nα), etc., reactions were not included.

The preequilibrium cross section in the exciton model depends inversely upon the value of the absolute square of the average matrix element of residual two-body interactions, $|M|^2$. The excitation energy and mass dependence of this matrix element was assumed to have the form

$$|M|^2 = KA^{-3}E^{-1}$$

as determined by Kalbach-Cline.[28] The value of the normalization factor K was taken to be equal to 150 MeV^3 as determined from fits to various sets of neutron experimental data.[29] This value is also in general agreement with the value of 100 MeV^3 determined by Kalbach-Cline. In order to reproduce (n,2n) and (n,3n) experimental results above 18-19 MeV, it was necessary to include preequilibrium contributions and to have the excitation-energy dependence given in the expression above.

Level-density parameters were calculated using the Gilbert-Cameron phenomenological prescription for deformed nuclei. That is, the level density parameter a is given by

$$a/A = 0.00917\ S + 0.12 \quad ,$$

where $S = S(Z) + S(N)$ is the shell correction factor obtained from the parameters of Cook.[30] The gamma-ray strengths were calculated using the giant dipole resonance model and were normalized to the experimental ratio of $2\pi\langle\Gamma_\gamma\rangle/\langle D\rangle$ for s-wave neutrons. Some slight adjustment of this normalization was made in the case of the compound nucleus ^{175}Lu in order to produce better agreement with the experimental data near the (n,2n) threshold. Gamma-ray emission involving E1, E2, and M1 transitions were allowed. Generally, we found that to include higher order transitions did not significantly affect the calculated results for isomeric cross sections.

The calculated cross sections for 8.5 to 20 MeV appear in Table II, along with calculated values for the ^{174}Lu isomeric-to-ground-state ratio produced by the (n,2n) reaction. The calculated ratio has been normalized to the average of the experimental results of Refs. 12, 13, 15, and 16 around 14 MeV. For reasons described in Sec. VI. D, our calculations failed to produce agreement with the experimentally determined isomer ratio values.

VI. DISCUSSION

A. Unnormalized Results

We have grouped in Fig. 2 the experimental values given directly by the authors. As can be seen in the figure, the isomeric cross-section results of Dilg,[12] Nethaway,[13] Qaim,[15] and Bayhurst[16] are consistent with each other, having an average value of about 600 mb. However, the results of Wille[11] are almost a factor of three greater than this value. We do not know the reason for this difference, but have assumed the Wille result to be in error. In Fig. 3 the experimentally determined total ^{174}Lu(n,2n) cross sections between 13 and 17 MeV are presented on an expanded scale. At 14.7 MeV the activation data of Qaim,[15] Dilg,[12] and Nethaway[13] appear to be consistent with the direct measurement results of Veeser.[17] The Frehaut measurements[6] lie somewhat higher, however, while the activation measurements of Bayhurst[16] are generally lower.

Only two sets of measurements, those of Veeser[17] and Bayhurst,[16] exist for the ^{175}Lu(n,3n) reaction. Between these two sets of data, differences generally between 10-20% exist.

TABLE II

CALCULATED $^{175}Lu(n,xn)$ CROSS SECTIONS

E_n (MeV)	$\sigma(n,2n)_{tot}$ (b)	$\sigma(n,3n)$ (b)	$R(m/g\ ^{174}Lu)$[a]	$\sigma(n,2n)^{m}$[b] (b)
8.5	0.412		0.198	6.4-2
9.	0.843		0.21	0.136
9.5	1.28			
10.	1.502		0.275	0.302
10.5	1.68			
11.	1.805		0.33	0.418
11.5	1.93			
12.	1.986		0.375	0.505
12.5	2.017			
13.	2.047		0.42	0.565
13.5	2.053			
14.	2.06		0.44	0.585
14.5	2.065			
15.	2.07		0.5	0.66
15.5	2.045			
16.	1.985	0.103	0.606	0.7
16.5	1.863	0.22		
17.	1.74	0.35	0.71	0.67
17.5	1.49	0.51		
18.	1.32	0.676	0.81	0.55
18.5	1.16	0.85		
19.	1.045	1.050	0.79	0.43
19.5	0.933	1.125		
20.	0.820	1.175	0.77	0.33

[a]The calculated value of 1.8 at 14.7 MeV has been normalized to the average experimental value of 0.483 to produce these results.

[b]Calculated with the renormalized R in column 4.

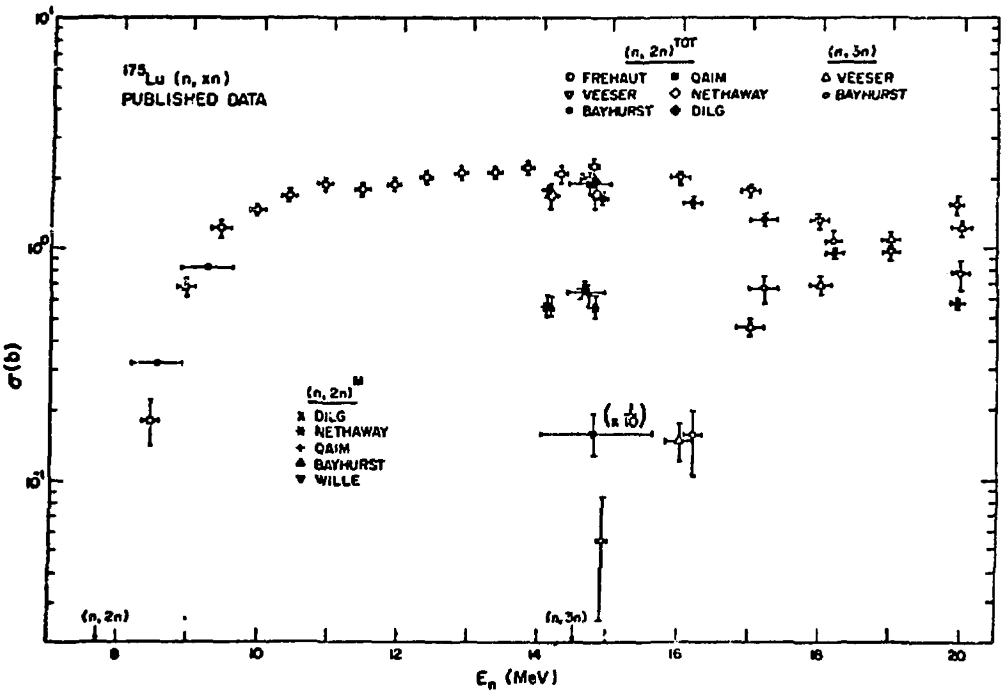

Fig. 2.
Experimental values given for the (n,2n), $(n,2n)^{174m}$Lu, and (n,3n) cross sections.

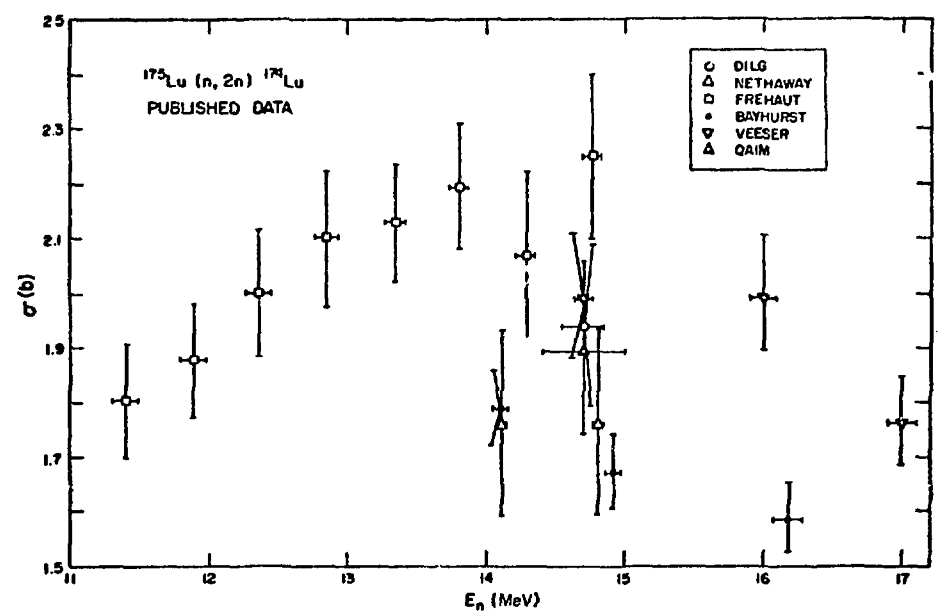

Fig. 3.
Experimental values given for the ^{175}Lu(n,2n)^{174}Lu cross sections from 11 to 17 MeV.

B. Normalized Results

Figure 4 shows the experimental results after application of the normalization factors described previously. Also included in Fig. 4 are our calculated cross sections (solid curves) along with uncertainty estimates (dashed curves) described in Sec. VII. A more detailed comparison of the calculated and renormalized (n,2n) results near 14 MeV is given in Fig. 5 on an expanded scale.

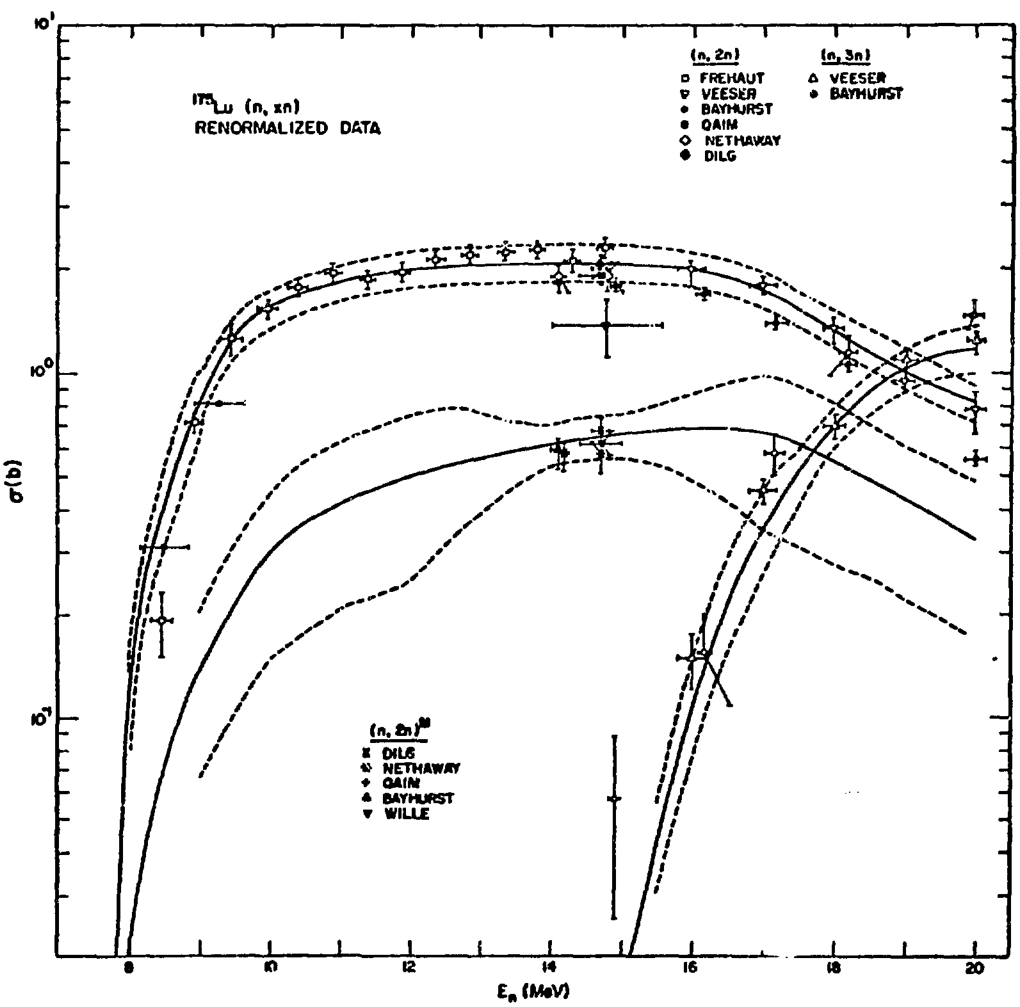

Fig. 4.
Normalized experimental (n,2n), $(n,2n)^m$, and (n,3n) cross sections along with the calculated results (solid lines) and error estimates (dashed lines).

After renormalization, the agreement around 14.7 MeV is slightly improved. However, the normalization factor raised slightly the Frehaut data in this energy region to make agreement with the Veeser data poorer. Although the Bayhurst (n,2n) data were also raised, there still exists a discrepancy with other (n,2n) results. At higher energies (18-20 MeV), this discrepancy persists with the Bayhurst data averaging about 35% lower than those of Veeser.

Renormalization of the Bayhurst (n,3n) results produced little change in the magnitudes of the measured cross sections, and the discrepancy with the Veeser data, noted in Sec. VI. A, still exists. (No normalization factor was applied to the absolute Veeser measurements.)

C. Comparison Between Total (n,2n) Experimental and Calculated Cross Sections: Recommended Values

The behavior of the calculated (n,2n) cross section near threshold is determined by compound nucleus effects, whereas at higher energies the preequilibrium contribution becomes important. Inclusion of the preequilibrium correction

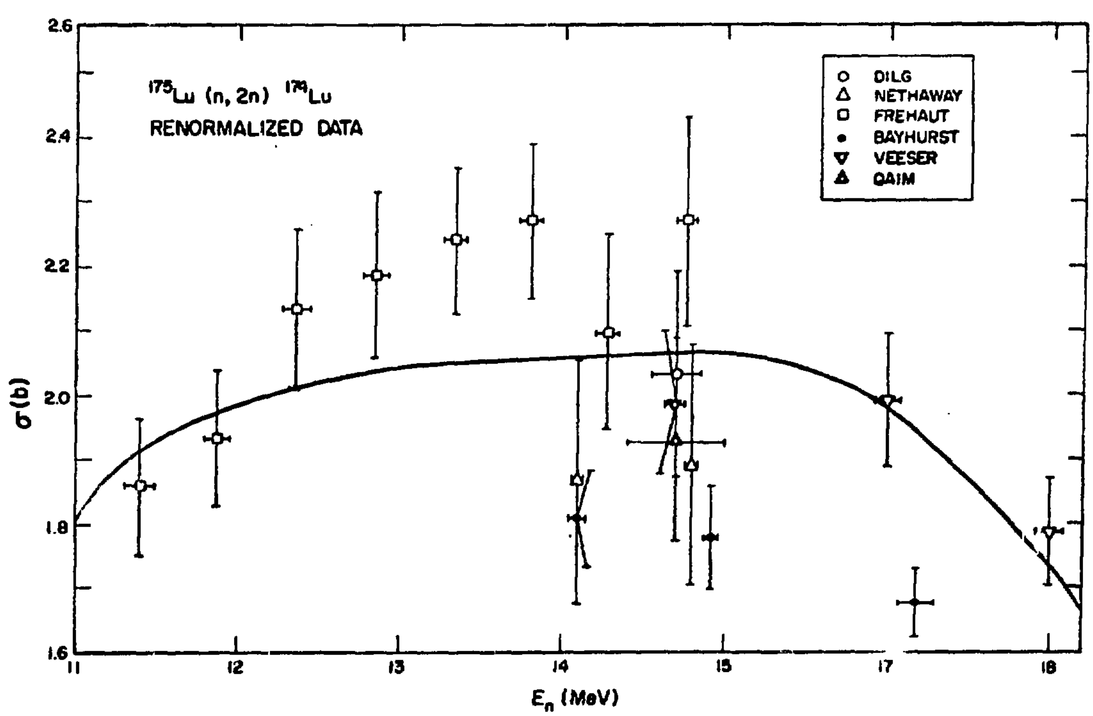

Fig. 5.
Normalized experimental and calculated (n,2n) values between 11 and 17 MeV.

has the effect of increasing the (n,2n) cross section at higher energies over that which results from compound nucleus considerations alone. The calculated curve in Fig. 4 agrees well with the Frehaut data at lower energies, and the Veeser results at higher energies. At 14.7 MeV, the calculated curve lies within 5-6% of the average of the Veeser results and the normalized Qaim, Dilg, and Nethaway results.

We believe activation measurements for Lu(n,xn) cross sections to be difficult owing to such problems as uncertainties in decay schemes, the half-lives involved, and backgrounds that may arise from the radioactive isotope ^{176}Lu. Similar activation measurements for ^{169}Tm, a nearby nucleus that is also strongly deformed, appear to be in better agreement with direct measurements.[4] Since direct measurements made with large scintillator tanks are free from the above difficulties, we feel the direct ^{175}Lu(n,2n) measurements of Frehaut (from threshold to 15 MeV) and those of Veeser (at higher eneriges) are probably more reliable. The calculated curve generally follows the (n,2n) cross section resulting from these two measurements, and we adopt it for the recommended values. Recommended (n,2n) values and uncertainties appear in Table III.

D. Experimental and Calculated ^{175}Lu(n,2n)^{174m}Lu Cross Sections: Recommended Values

In contrast to the good agreement obtained between experimental and calculated results for the total (n,2n) cross sections, our calculated isomeric state ratio of 1.3 at 14.7 MeV disagrees significantly with the average of the measured results (Bayhurst, Qaim, Nethaway, and Dilg), which is 0.483. In our calculations of this isomer ratio, we included less than 20 levels in the residual ^{174}Lu nucleus. Since ^{174}Lu is deformed, it has been recently determined by Nethaway and Gardner[31] that the first few rotational bands in ^{174}Lu must be enumerated up to spins of 12 or 13 in order to fit the experimental data at 14.7 MeV. In their calculation, this required that 90 levels be included for ^{174}Lu in order to obtain agreement. Since we have not attempted a calculation of this magnitude, we have normalized our calculated isomer-to-ground-state ratio to the average of the experimental values described above (R = 0.483). Using this normalization factor along with the total calculated (n,2n) cross section, we have obtained the curve for the ^{175}Lu(n,2n)^{174m}Lu cross section shown in Fig. 3. The ^{175}Lu(n,2n)^{174m}Lu cross section derived in this manner also appears in Table III.

E. Experimental and Calculated $^{175}Lu(n,3n)$ Cross Sections: Recommended Values

As seen in Fig. 4, our calculated (n,3n) cross sections are in good agreement with the data of Veeser from threshold to 20 MeV. The values of Bayhurst lie generally higher than either the Veeser values or the calculated curve. Again, for the reasons discussed in Sec. VI. D, we have chosen to rely mainly on the Veeser (n,3n) cross sections in our evaluation. Since the calculated curve follows generally the Veeser results, we adopt it for the recommended values. These values are tabulated in Table III.

TABLE III

RECOMMENDED VALUES AND ESTIMATED ERRORS

E_n (MeV)	n,2n (b)	$n,2n^m$ (b)	n,3n (b)
7.703	0.		
7.8	4.0-2 ± 1.-2	0.	
8.	0.1 ± 2.5-2	2.-2 ± 1.-2	
8.5	0.412 ± 0.103	7.5-2 ± 3.75-2	
9.	0.843 ± 0.211	0.135 ± 6.75-2	
9.5	1.28 ± 0.192	0.210 ± 0.105	
10.	1.502 ± 0.225	0.3 ± 0.15	
10.5	1.68 ± 0.252	0.365 ± 0.182	
11.	1.805 ± 0.271	0.420 ± 0.21	
11.5	1.93 ± 0.290	0.465 ± 0.232	
12.	1.986 ± 0.298	0.5 ± 0.25	
12.5	2.017 ± 0.303	0.54 ± 0.23	
13.	2.047 ± 0.307	0.565 ± 0.175	
13.5	2.053 ± 0.308	0.595 ± 0.125	
14.	2.06 ± 0.309	0.62 ± 0.09	
14.5	2.065 ± 0.31	0.65 ± 0.1	
14.53	2.065 ± 0.31	0.65 ± 0.1	0.
15	2.07 ± 0.311	0.66 ± 0.1	1.4-2 ± 4.2-3
15.5	2.045 ± 0.307	0.68 ± 0.14	4.4-2 ± 1.3-2
16.	1.985 ± 0.298	0.69 ± 0.21	0.103 ± 3.1-2
16.5	1.863 ± 0.279	0.68 ± 0.26	0.22 ± 6.6-2
17.	1.74 ± 0.26	0.665 ± 0.315	0.35 ± 0.105
17.5	1.49 ± 0.22	0.615 ± 0.305	0.51 ± 9.-2
18.	1.32 ± 0.198	0.55 ± 0.275	0.676 ± 0.1
18.5	1.16 ± 0.174	0.49 ± 0.245	0.85 ± 0.13
19.	1.045 ± 0.157	0.43 ± 0.215	1.05 ± 0.16
19.5	0.933 ± 0.14	0.37 ± 0.185	1.125 ± 0.17
20.	0.82 ± 0.12	0.33 ± 0.165	1.175 ± 0.18

VII. COMPARISON WITH ENDF/B VALUES

Figure 6 compares our recommended values for ^{175}Lu(n,2n) and ^{175}Lu(n,3n) cross sections to those given in ENDF/B-IV (MAT = 1032), denoted by the dots and squares, respectively. Although below the (n,3n) threshold the two evaluations agree nicely, at higher energies the ENDF/B-IV values fail to reproduce the experimental (n,2n) or (n,3n) data.

VIII. UNCERTAINTIES IN THE RECOMMENDED VALUES

We have made rough estimates of the uncertainty in the calculated curves shown in Fig. 4 for the ^{175}Lu(n,2n), ^{175}Lu(n,2n)^{174m}Lu, and ^{175}Lu(n,3n) cross sections and have indicated these estimates by the dashed curves. (See also

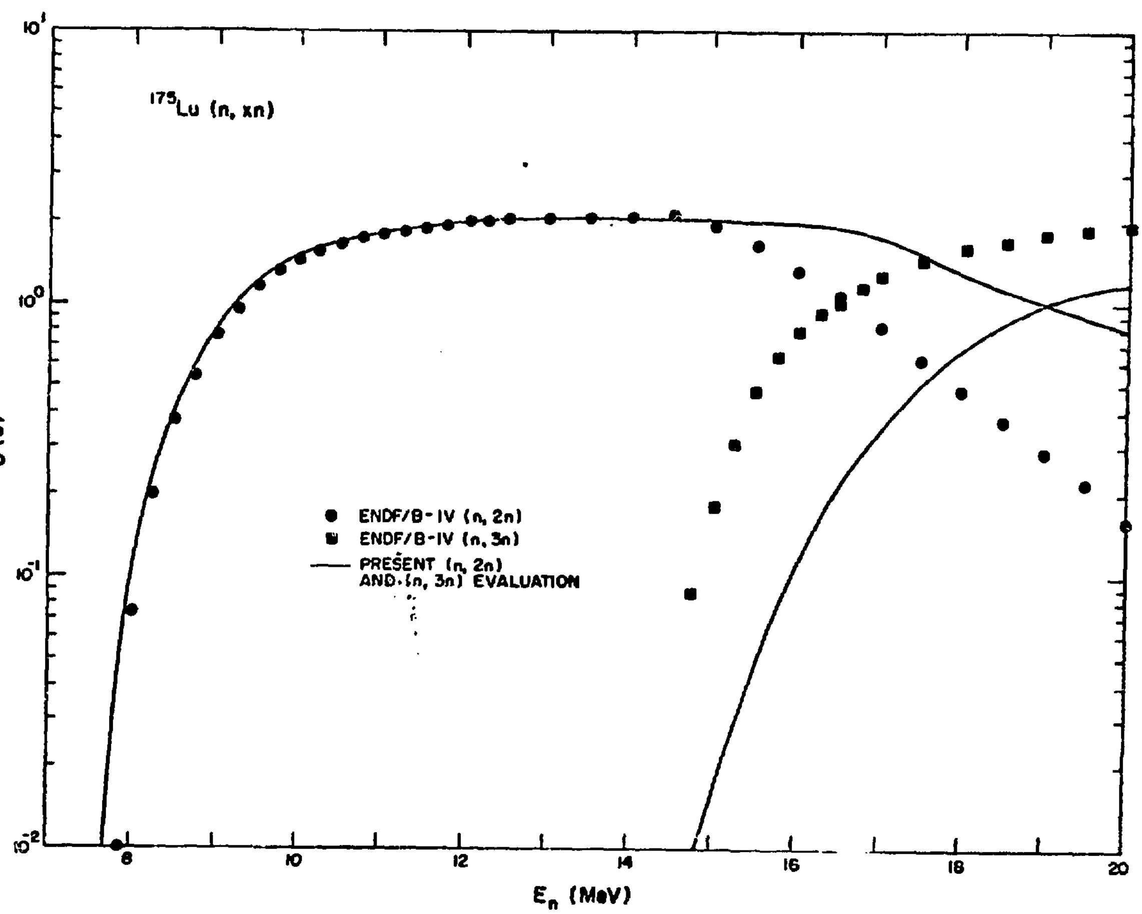

Fig. 6.
Comparison of our recommended (n,2n) and (n,3n) values with those in ENDF/B-IV.

Table III.) In our error estimates, we were influenced by uncertainties in the input parameters to the model calculation and their effects upon the calculated cross section. Also, the error was determined partially by the spread in experimental results.

For the total (n,2n) cross section, we assign a $\pm$ 25% uncertainty from threshold (7.703 MeV) to 9 MeV, and a $\pm$ 12.5 % uncertainty from 9 to 20 MeV. These error bands generally encompass all the total (n,2n) data although the measurements of Frehaut and Bayhurst sometimes lie, respectively, at the upper and lower limits of these estimated curves. A $\pm$ 35% uncertainty was assigned for the (n,3n) cross section from threshold (14.53 MeV) to 17 MeV, while from 17 to 20 MeV, a $\pm$ 15% uncertainty was assigned. Again, most of the measured (n,3n) data fall within these bounds, an exception being the datum of Bayhurst at 19.18 MeV, which lies significantly outside these bounds.

For the (n,2n) isomeric state cross section, the assignment of errors is more subjective and uncertain owing to the calculational problems described in Sec. VI. D. In the region 14-15 MeV where several sets of data produce consistent results, a $\pm$ 15% uncertainty was assigned. (The error bands exclude the data of Wille, which appear to be in error.) From 13 to 14 MeV and from 15 to 16 MeV, a $\pm$ 30% uncertainty was assigned. In all other energy regions, the uncertainty was increased to $\pm$ 50%.

IX. CONCLUSIONS

We have evaluated the ^{175}Lu(n,2n), ^{175}Lu(n,2n)^{174m}Lu, and ^{175}Lu(n,3n) reactions through application of a consistent set of normalization parameters to the experimental data and through use of statistical-preequilibrium calculations. Our examination of the measured data has shown that for total (n,xn) reactions on ^{175}Lu, some discrepancies exist between direct and activation measurements in the region of overlap. Because of the additional uncertainties in ^{175}Lu activation measurements due to uncertainties in decay schemes, half-lives, and contaminent backgrounds, we have relied more heavily on direct measurements made with large scintillator tanks for the recommended values.

The statistical-preequilibrium calculations are in good agreement with the measured ^{175}Lu(n,2n) and (n,3n) cross sections, particularly the scintillator tank data. In our calculation of the ^{175}Lu(n,2n)^{174m}Lu reaction, however, difficulties arise from the deformation properties of ^{174}Lu and prevent reasonable agreement of calculated and experimental values. A more extensive calculation incorporating additional levels for ^{174}Lu would be required to improve the agreement.

In light of the experimental and calculational difficulties discussed here, a more precise evaluation of ^{175}Lu(n,xn) cross sections is dependent on more accurate experimental results (for both the total and isomer cross sections), along with more realistic and detailed calculations, particularly with regard to the ^{175}Lu(n,2n)^{174m}Lu reaction.

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