Lawrence Livermore Laboratory

STATUS REPORT TO ERDA
NUCLEAR DATA COMMITTEE

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LAWRENCE LIVERMORE LABORATORY

A. STANDARDS

1. Fission Cross Sections of ^{235}U and ^{238}U Near 14 MeV. (G. W. Carlson)

Measurements of the fission cross sections of ^{235}U and ^{238}U near 14 MeV are being planned. The goal of the measurements will be to determine the absolute cross sections with an uncertainty less than 2% and to measure the shape of the cross sections versus neutron energy from 13.7 to 15 MeV. The measurements will be made using the LLL Rotating Target Neutron Source (RTNS).

B. NEUTRON DATA APPLICATIONS

1. High Energy Fission Cross Section Ratio Measurements. (J. W. Behrens, G. W. Carlson, and J. C. Browne)

We have completed the neutron-induced fission cross section measurements on a series of plutonium isotopes using ionization fission chambers at the LLL 100-MeV electron linear accelerator. Ratios of the cross sections of ^{239}Pu , ^{240}Pu , ^{241}Pu , and ^{242}Pu relative to ^{235}U have been measured as functions of neutron energy over the range .001 to 30 MeV, except where limited by low cross sections on the threshold isotopes. We normalized the results independent of other measurements by using the threshold cross section method. These ratio measurements¹⁻³ were obtained in a manner similar to the series of uranium isotopes

¹G. W. Carlson and J. W. Behrens, Fission Cross Section Ratio of ^{239}Pu to ^{235}U from 0.1 to 30 MeV, Lawrence Livermore Laboratory, Rept. UCID-16981 (1975).

²J. W. Behrens and G. W. Carlson, Measurement of the Neutron-Induced Fission Cross Section of ^{241}Pu Relative to ^{235}U from 0.001 to 30 MeV, Lawrence Livermore Laboratory, Rept. UCRL-51925 (1975).

³J. W. Behrens, J. C. Browne, and G. W. Carlson, Measurements of the Fission Cross Sections of ^{240}Pu and ^{242}Pu Relative to ^{235}U , Lawrence Livermore Laboratory, Rept. UCID-17047 (1976).

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which were presented at the Conference on Nuclear Cross Sections and Technology, March 3-7, 1975⁴.

2. Fission Cross Sections of ^{233}U , ^{239}Pu and ^{241}Pu relative to ^6Li .
(J. B. Czirr, J. W. Behrens, and G. W. Carlson)

We have obtained fission cross section data for ^{241}Pu , ^{239}Pu and ^{233}U in the energy range from 10 eV to 70 keV. The incident neutron spectrum was measured with a thin ^6Li -glass scintillator and energies were obtained by time of flight. The cross sections will be normalized to accepted thermal values by using similar data obtained in the thermal to keV range. The results will be separated in broad energy bins to improve the statistical precision.

3. Fission $\bar{\nu}$ Measurements. (R. E. Howe and T. W. Phillips)

Measurement of $\bar{\nu}$ for $^{235}\text{U}(n,f)$ in the MeV region ($E_n \leq 25$ MeV) is nearing completion. Preliminary results are shown in Figure B-1. These data were normalized to the recommended prompt $\bar{\nu}$ values of Manero and Konshin⁵ in the energy range 0.5 to 1.0 MeV but using a prompt $\bar{\nu}$ for ^{252}Cf (spontaneous fission) = 3.724. Work is currently underway to normalize our results to the thermal energy value of $\bar{\nu}$ for ^{235}U , to calibrate our neutron energy scale, and to investigate the influence of some potential systematic effects on our results. These latter are not expected to exceed the statistical errors in $\bar{\nu}$ shown in the figure.

Current plans are to proceed with prompt $\bar{\nu}$ measurements at MeV energies for other isotopes when the ^{235}U work is completed.

4. Fission Cross Section of ^{245}Cm . (J. C. Browne)

The fission cross section of ^{245}Cm has been measured from 0.006 eV to 20 eV using an isotopically-pure 3- μg sample of ^{245}Cm obtained by Savannah River Laboratory from the decay of ^{249}Bk . These data, which were taken at a 3.5-m flight path at the LLL 100-MeV linac, are presently being analyzed.

⁴J. W. Behrens, G. W. Carlson, and R. W. Bauer, "Neutron-Induced Fission Cross Sections of ^{233}U , ^{234}U , and ^{238}U with Respect to ^{235}U , Proc. Conf. Nuclear Cross Sections and Technology, Washington, D.C., March 3-7, 1975, Vol. 2, p. 591.

⁵Manero, Rl, Konshin, V. A., Atomic Energy Review 10, (1972) 637.

Fig. B-1. Prompt $\bar{\nu}$ for ^{235}U (n,f) versus incident neutron energy. Data have been corrected for deadtime losses and background neutrons. Horizontal error bars represent the inclusive neutron energies used in the calculation of each data point.

5. Measurements of the ${}^7\text{Li}(p,n_0){}^7\text{Be}$ and ${}^7\text{Li}(p,n_1){}^7\text{Be}^*$ Cross Sections Between 4.2 and 26 MeV. (S. M. Grimes, C. H. Poppe, J. D. Anderson, J. C. Davis and C. Wong)

Cross sections for the ${}^7\text{Li}(p,n_0){}^7\text{Be}$ and ${}^7\text{Li}(p,n_1){}^7\text{Be}^*$ reactions have been measured over the energy ranges 4.25 to 12 MeV and 15.1 to 25 MeV in 1-MeV steps. The data span the angular range 3.5° to 159° and were obtained with the LLL cyclograaff and multi-detector TOF spectrometer. Because the thickness of the Li target was known only roughly, the absolute cross sections were fixed by normalizing them to the value measured by Gibbons and Macklin⁶ at 5 MeV. This normalization agreed to within 4% with that inferred from a measurement of the ${}^7\text{Li}(p,n_0)$ and ${}^7\text{Li}(p,n_1)$ cross sections at forward angles (where the n_0 and n_1 neutron groups are higher in energy than any neutrons from ${}^{19}\text{F}(p,n)$) with a LiF target of known thickness.

At the highest energies ($E \gtrsim 20$ MeV), the n_0 and n_1 groups were incompletely resolved at a flight path of 10.8 m; the separate cross sections were obtained by using a peak fitting routine. This procedure was tested by performing 0° measurements with a flight path of 30 m; good agreement between the cross sections obtained in the two different measurements was observed. The forward angle ratio of neutrons in the n_1 group to those in the n_0 group is larger than 25% for all energies above 7 MeV, reaching a peak of 55% at 9 MeV. This ratio then falls to about 30% near 17 MeV and is 35% at 26 MeV.

It is concluded that the large n_1 cross section and the large flux of lower energy neutron make the ${}^7\text{Li}(p,n)$ reaction inappropriate as a neutron source for some applications; however, the large forward angle cross section (30 mb/sr at 26 MeV) makes it attractive in situations where large fluxes of lower energy neutrons do not pose a problem.

6. Calculations of Neutron Reactions with ${}^{238}\text{U}$. (D. G. Gardner)

The following is an abstract of an LLL Chemistry Department Technical Note No. 75-48.

"Preliminary calculations are presented for various neutron reactions with ${}^{238}\text{U}$ over the incident energy range 10 keV to 5 MeV. The statistical model calculations were performed with the COMNUC-CASCADE code, and direct inelastic scattering input was provided by the coupled-channel codes JUPTTOR and FOURPLUS. Excitation functions are given for the total, elastic, inelastic, capture and fission reactions as well as inelastic scattering to the first 2^+ and 4^+ states.

⁶J. H. Gibbons and R. L. Macklin, Phys. Rev. 114, 571 (1959).

Some angular distributions are shown for elastic scattering to the 2+ and 4+ states. Comparisons are provided between the present calculations and the ENDL and ENDF/B-IV evaluated data libraries."

7. An Investigation of the Dependence of γ -Ray Spectral Shape on the Averaging Interval Size for the $^{181}\text{Ta}(n,\gamma)$ Reaction.
(M. L. Stelts* and J. C. Browne)

The γ -ray spectra for the $^{181}\text{Ta}(n,\gamma)$ reaction were measured from 2 eV to 90 keV neutron energy at the LLL 100-MeV linac using a three-crystal (Ge(Li)-NaI) spectrometer. The γ -ray spectra were unfolded using the measured δ -function response of the spectrometer as described in Report No. UCRL-77467 (accepted for publication in Nuclear Instruments and Methods) and averaged into broad neutron energy bands. The results are shown in Fig. B-2. The spectra are identical (to within experimental error) except in the γ -ray energy region from 5 to 6 MeV where there is a systematic decrease in strength as the neutron energy increases.

8. Calculations of the Neutron Emission Spectra from Materials Bombarded with 14-MeV Neutrons. (L. F. Hansen, S. M. Grimes, R. J. Howerton and J. D. Anderson)

Neutron emission spectra from targets bombarded by 14-MeV neutrons have been calculated using three nuclear models. The elements studied included Al, Fe, Cu, Ni, and Nb and were selected because of their potential importance in fusion reactor design and because measured cross sections and calculated cross section libraries are available for comparison with the calculations.

The main features of the calculation are: 1) Contributions from statistical, preequilibrium and direct reactions are included to achieve a good fit to the data; 2) It does not make use of experimental neutron data to generate the cross sections; 3) It does make use of nuclear reaction systematics and deformation parameters, as inferred from charged particle measurements, to predict the neutron inelastic spectra above 6 MeV. For 14-MeV neutrons incident on a nucleus, the statistical model predicts quite adequately the low energy part of the emitted spectrum, but underestimates the production of higher energy neutrons. These neutrons are the result of pre-equilibrium processes or direct reactions. The pre-equilibrium processes have been calculated using the hybrid model of Blann where it is assumed that the compound nucleus reaches equilibrium through a series of two-body interactions. The

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Fig. B-2. Results of unfolding $^{181}\text{Ta}(n,\gamma)$ spectra for the neutron energy region between 20 eV and 9×10^4 eV. Background has been subtracted, detector efficiency and absolute normalization applied to give absolute intensities in photons/MeV/1000 captures.

direct inelastic (n,n') cross sections to the lower excited levels were calculated using the Oregon State University's Coupled-Channel-Code (C-CH-C) assuming a collective model for the interactions. Contributions to the inelastic neutron spectrum from the ($n,2n$) cross section were calculated assuming the emission of the second neutron to be statistical. The results of this calculation are shown in Figure B-3.

A complete summary of the results and their comparison with those predicted by the ENDF/B-IV and ENDL neutron evaluated libraries together with experimental measurements available for the above nuclei can be found in UCRL-77778*. The calculations reproduce the experimental results fairly well; since no experimental neutron data were used to generate them and the calculations are based in nuclear models well supported by experiments, this suggests that the predicted secondary spectra from other materials bombarded with 14-MeV neutrons, where no measurements are available, may be equally accurately predicted.

9. Comparison Between Measurements and Calculations Using the ENDF/B-IV Neutron Library for Structural Materials Used in Fusion Reactors. (L. F. Hansen, C. Wong, T. Komoto and J. D. Anderson)

Measurements of the integral neutron energy spectra from C, O, Al, Ti and Fe, obtained using the pulsed sphere and time-of-flight techniques, were compared with the predictions of the most recent version of the ENDF/B-IV library. Spherical assemblies of the above materials ranging from 1 to 5 mean-free-paths were bombarded with a centered 14-MeV (nominal) neutron source. Since these materials have been used by different authors⁷ in the design of the CTR fusion blanket structures and their calculations have been carried out with the preceding version III of the ENDF/B library, the above integral measurements were also calculated with this early library.

Table B-1 gives the calculated integrals with versions III and IV for Al, Ti and Fe (the complete results of these measurements can be found in UCRL-77270[†]). The integrals are given in neutrons per source neutron for three neutron energy intervals: 15 MeV to 10 MeV, 10 to 5 MeV and 5 to 2 MeV. Use of the ENDF/B-IV cross sections resulted in larger calculated total integrals and closer agreement with the measurements. Discrepancies of 10-20% still exist for the 2-10 MeV region for the thicker spheres in Table I, but version IV of the library represents a clear improvement over the ENDF/B-III library, where discrepancies of as much as a factor of 2 existed between measurements and

*This work has been accepted for publication by Nuc. Sc. & Eng. (1976).

⁷R. G. Alsmiller, Jr., R. T. Santoro, J. Barish and T. A. Gabriel, Nuc. Sci. and Eng. 57, 122 (1975).

[†]The paper has been accepted for publication in Nuc. Sci. and Eng. To be published 1976.

Fig. B-3. Calculations of the compound nucleus cross sections for Fe, Ni, and Cu (---); the respective pre-equilibrium contribution added to each of the above cross sections (—); direct contribution to the inelastic (n,n') cross sections for the lower excited levels in these nuclei (///).

Table B-1. Measured and calculated Integrals with Versions III and IV of the ENDF/B Library for the energy intervals 15-10, 10-5 and 5-2 MeV. The integrals are given in neutrons/source neutron.

MATERIAL	mfp	θ	ENERGY INTERVAL	EXPERIMENT $\pm 7\%$	TART ENDF/B-IV	TART ENDF/B-III
ALUMINUM	0.9	30°	15-10	4.603-02	4.615-02	4.971-02
			10-5	0.398-02	0.448-02	0.152-02
			5-2	<u>0.785-02</u>	<u>0.693-02</u>	<u>0.554-02</u>
			TOTAL	5.786-02	5.756-02	5.677-02
TITANIUM	1.2	30°	15-10	4.083-02	4.401-02	5.237-02
			10-5	0.319-02	0.233-02	0.088-02
			5-2	<u>1.072-02</u>	<u>0.774-02</u>	<u>0.593-02</u>
			TOTAL	5.474-02	5.408-02	5.918-02
IRON	0.9	30°	15-10	4.854-02	4.915-02	4.970-02
			10-5	0.275-02	0.276-02	0.091-02
			5-2	<u>0.810-02</u>	<u>0.704-02</u>	<u>0.482-02</u>
			TOTAL	5.939-02	5.895-02	5.543-02

calculations. Fig. B-4 shows the measured and calculated energy spectra with library IV for Al, Ti and Fe.

10. Measurements and Calculations of the Gamma Spectra from Nitrogen for a 14-MeV Neutron Source. (L. B. Hansen, T. Komoto, E. F. Plechaty, B. A. Pohl and C. Wong)

In the last USNDC report, UCID-16725 (March 11, 1975), measurements of the gamma spectra from 0.5, 1.0 and 3.0 mfp nitrogen bombarded with 14-MeV neutrons were reported. The measurements were done using the pulsed sphere transmission and time-of-flight techniques using NE213 scintillators at angles of 26° and 120° for flight paths ranging between 7 m and 10 m. At that time calculations with the ENDF/B-IV neutron-photon library were also reported, where the recoil electron response of the detector was calculated with the Monte Carlo Photon Transport code TORTE. The response function of the detector has been recalculated using a Monte Carlo Electron-Photon Transport code TCRT-EP. This code follows electrons and positrons from Compton, and photons from photoelectric and pair interactions until they have either stopped or have left the detector system. In the present calculations, a correction factor for the air absorption of the source neutrons was included which was not used in the original calculations. Also a new measurement for 7.0 mfp nitrogen was carried out.

The integrals of the measured and calculated spectra, corresponding to the total number of electron pulses above bias per source neutron, are given in Table B-2. The values have been normalized to a flight path of 10 m. The measured integrals for the 26° and 120° detectors, normalized to the same flight path of 10 m, show differences smaller than the quoted experimental errors of 7.5% and hence have been averaged for comparison with the calculations. The discrepancies are much less than 20%. A fraction of these discrepancies may be attributed to the use of the calculated detector efficiency which is between 5 and 8.0% too high.

11. Measurement of (n,xp), (n,xd) and (n,x α) Cross Sections for ^{27}Al , ^{46}Ti and ^{48}Ti at 14 MeV. (S. M. Grimes, R. C. Haight and J. D. Anderson)

Cross sections for (n,xp), (n,xd) and (n,x α) reactions induced by 14-MeV neutrons on ^{27}Al , ^{46}Ti and ^{48}Ti have been measured with a quadrupole spectrometer. Particles with energies as low as 0.8 MeV were detected. Large sub-Coulomb barrier peaks are found in the proton spectra from ^{27}Al and ^{46}Ti but not for that of ^{48}Ti ; alpha particle and deuteron spectra do not show such a peak. The presence or absence of such a peak is related to the importance of the (n,n'p) reaction for a given isotope. Enhancement of the total charged particle cross section

Fig. B-4. Measured (+) and calculated (line) energy spectra using ENDF/B-IV for 0.6 and 2.6 mfp aluminum, 1.2 and 3.5 mfp titanium, and 0.9 and 4.8 mfp iron.

Table B-2. Measured integrals of the gamma-ray spectra from nitrogen as a function of mean free path, and calculated integrals using ENDF/B-IV. The integrals correspond to the total number of electron pulses above 340 keV electron bias per source neutron.

θ	mfp	Measured*	Calculated*	Discrepancy [†] (%)
		$\times 10^{-8}$ $\pm 7.5\%$	ENDF/B-IV $\times 10^{-8}$	
26	0.5	3.947	4.815	19
120	0.5	4.199	4.850	
26	1.0	5.661	6.639	13
120	1.0	6.132	6.743	
30	3.0	7.417	7.867	4.5
120	3.0	7.674	7.908	3.6
26	7.0	2.935	2.833	

*Normalized to 10 m flight path.

†Discrepancy between the calculated and measured integrals.
(The ratio was calculated for the respective average values from the two angles.)

by about 65% through such reactions is found for ^{27}Al and ^{46}Ti . Such charged particle cross sections are important in estimating materials damage problems in fusion reactors. Nuclear transmutation and hydrogen and helium accumulation are directly related to charged particle cross sections. It appears that the presence or absence of a large $(n,n'p)$ cross section (because of the $(n,2n)$ Q value) could be an important consideration in the choice of materials for fusion reactor construction.

12. Reaction Rates In A Uranium Pile Surrounding A 14-MeV Neutron Source: Calculations of the Weale Experiment. (R. C. Haight, J. D. Lee and J. A. Maniscalco)

A report (UCRL-77364, Rev. 1) on this subject has been submitted to Nuclear Science and Engineering. Results of the calculation are summarized in Table B-3. The abstract of this paper follows:

"To validate the neutronics analysis of hybrid fusion-fission reactor blankets, calculations were made of an experiment by Weale *et al.*,⁸ where a 14-MeV neutron source was surrounded by a natural uranium metal pile. The evaluated nuclear data libraries, ENDL and ENDF/B, were used. The calculated parameters were found to be in closer agreement for present versions* of these libraries than for preceding versions; however, there were still 15% differences in the $^{235}\text{U}(n,f)$ and $^{238}\text{U}(n,f)$ reaction rates. The present version of ENDL gives results that are the closest to the experimental values for these reactions. For the $^{238}\text{U}(n,\gamma)$ reaction, the calculations with the ENDF/B libraries are closer to the measured values. Both the ENDL and ENDF/B evaluations, however, fail to calculate correctly the neutron leakage or derived values for the $^{238}\text{U}(n,2n)$ and $^{238}\text{U}(n,3n)$ reaction rates. The spatial variations of the $^{235}\text{U}(n,f)$, $^{238}\text{U}(n,\gamma)$, $^{238}\text{U}(n,f)$ and $^{239}\text{Pu}(n,f)$ reaction rates show that the penetration of high-energy neutrons in the pile is better described by the calculation with ENDL, which gives a greater penetration. The effects of resonance self-shielding were investigated and found to require a correction much smaller than the differences between calculations with different data libraries."

⁸J. W. Weale, H. Godfellow, M. H. McTaggart, and M. L. Mullender, J. Nucl. Energy A/B 14, 91 (1961).

*Present version ENDF/B-IV.

Table B-3. Reactions per 14-MeV Source Neutron Integrated over the Pile

Reaction	Calculation				Experiment ^a
	Historical Libraries		Current Libraries		
	ENDF/B-III	ENDL(old) ^b	ENDF/B-IV	ENDL(new) ^c	
²³⁵ U(n,f)	0.226	0.287	0.228	0.266	0.281 ± 0.017
²³⁵ U(n,γ)	0.055	0.064	0.057	0.061	-
²³⁸ U(n,f)	0.828	1.31	0.949	1.11	1.18 ± 0.06
²³⁸ U(n,γ)	4.03	4.63	4.27	4.36	4.08 ± 0.24
²³⁸ U(n,2n)	0.328	0.417	0.358	0.388	0.277 ± 0.008 ^d
²³⁸ U(n,3n)	0.173	0.179	0.176	0.195	0.327 ± 0.052 ^d
Leakage	0.284	0.587	0.296	0.504	0.42 ± 0.02

^aIntegrated reaction rates were determined by drawing smooth curves through points measured at various positions in the pile and then integrating. The errors are those assigned in Ref. 8.

^bENDL (old) is the version of the LLL Evaluated Nuclear Data Library dated January 25, 1974.

^cENDL (new) is the version of ENDL dated February 18, 1975.

^dExperimental values were actually derived based on the 14-MeV flux as determined by the $^{63}\text{Cu}(n,2n)$ ^{62}Cu results and on an assumed value of the $^{238}\text{U}(n,2n)$ ^{237}U or $^{238}\text{U}(n,3n)$ ^{236}U cross section at 14 MeV.

C. DATA COMPILATION PROGRAM

1. Recent Evaluations for Neutron-Induced Reaction Data. (R. J. Howerton)

At the request of the CSEWG, complete evaluations for ^{236}U , $^{242,243}\text{Pu}$, $^{241,242}\text{m}$, ^{243}Am , $^{244,245,246,247,248}\text{Cm}$, $^{249,250,251,252}\text{Cf}$ were done for inclusion in the ENDF/B-V data file. The low neutron energy (<1 keV) data, for the transplutonium isotopes are based on the Savannah River Laboratory partial evaluation done by Benjamin. At higher energies most of the data are based on nuclear systematics for reaction and energy ranges where no measurements have been reported.

The LLL ENDL data file has been upgraded for all the uranium and plutonium isotopes. $^{231,233}\text{Th}$ have been added as complete evaluations. The fission cross sections have been modified by basing the ^{235}U fission cross sections for neutron energies greater than 800 keV on the Czirr-Sidhu measurements;⁹ and for $^{233,234,236,238}\text{U}$, $^{239,240,241,242}\text{Pu}$ the Behrens-Carlson ratios¹⁻⁴ were applied to the adopted ^{235}U fission cross section. Forty-six standard spherical critical assemblies fueled by ^{235}U , ^{233}U and ^{239}Pu and reflected by various materials were calculated using the TART Monte Carlo neutronics code. The resulting mean value for k_{eff} was .99934. To test the high energy (14-15 MeV) data, LLL pulsed spheres were calculated with excellent agreement with experiment.

A new version of the LLL ENDL data file in the ENDF/B format was distributed to LASL, NNCSC, and RSIC. The file is available from either of the latter two facilities.

A revised version of UCRL-50400, Vol. 6, "Tables and Graphs of Photon Interaction Cross Sections from 1.0 keV to 100 MeV Derived from the LLL Evaluated Nuclear Data Library," was distributed. Part A of Vol. 15 of UCRL-50400, "The LLL Evaluated Nuclear Data Library (ENDL): Evaluation Techniques, Graphical Displays and Descriptions of Individual Evaluations," was distributed. Volume 14 of UCRL-50400, "TARTNP: A Coupled Neutron-Photon Monte Carlo Code," was distributed. A revision of Vol. 5 of UCRL-50400, "CLYDE: A Nuclear Data-Processing Computer Program for Producing Calculational Constants," was distributed.

New editions of Volumes 2, 3, 7, 8, 10, and 16 of UCRL-50400 are being prepared. These are respectively the bibliography (Vol. 2), indexes (Vol. 3), graphical data (Vols. 7 and 8), and tabulation of experimental data (Vol. 10) of the Experimental Cross Section Information Library (ECSIL), and tables and graphs of 175 neutron group constants derived from ENDL (Vol. 16).

⁹J. B. Czirr and G. S. Sidhu, Nucl. Sci. Eng. 57, 18 (1975); Nucl. Sci. Eng. 58, 371 (1975).

D. BASIC PHYSICS

1. An Upper Limit On A Time-Reversal Non-Invariant Part Of Wigner's Random Matrix Model. (H. S. Camarda)

A report (UCRL-77501) has been accepted for publication in Physical Review C. The following is the abstract for this paper.

"The results of a Monte Carlo investigation and comparison with experimental data of Wigner's random matrix model with differing amounts of a time reversal non-invariant part are presented. With $H_{ij} = R_{ij} + iyI_{ij}$, calculations were performed with $y = 0.00, 0.05, 0.10, 0.20, 0.50$, and 1.00 using 40×40 matrices and $y = 0.00, 0.05$, and 0.10 with 80×80 matrices. After unfolding the density variation of the eigenvalues the behavior of the Dyson-Mehta Δ_3 statistic was examined for different values of y . The behavior of the reduced widths, which has also been examined in a previous calculation by Rosenzweig, Monahan, and Mehta, was found to be considerably more sensitive to small y values than the Δ_3 statistic. Thus the reduced width data can place a much lower limit on y than the level spacing information. A comparison to the calculations performed here with recently collected high quality neutron resonance data gives $y < 0.05$ at the 99.7% confidence level. It is also shown that the same value of the Dyson-Mehta Δ_3 statistic results when the matrix elements of Wigner's model are chosen from a gaussian or flat distribution."

2. Neutron-Capture Cross Sections for ^{186}Os and ^{187}Os and the Age of the Universe. (J. C. Browne and B. L. Berman)

We have measured the neutron-capture cross sections for ^{186}Os and ^{187}Os in the energy range up to 150 keV which corresponds to stellar temperatures up to about 18×10^8 °K. These cross sections (shown in Fig. D-1) enable us to calibrate the $^{187}\text{Re} \rightarrow ^{187}\text{Os}$ β -decay clock which can be used to determine the age of the universe. These results, which have been submitted to Nature in Report No. UCRL-77967, yield $19.6 \pm 4 \times 10^9$ years for the age of the universe which is larger than results from other dating techniques.

Fig. D-1. The neutron-capture cross sections versus laboratory neutron energy for ^{186}Os and ^{187}Os . The horizontal bar represents the size of the energy bin into which the data have been averaged. (The energy resolution of the actual measurement was much better.) The uncertainty for each data point lies within the plotted symbol and typically is 5% at 30 keV.

3. ^{187}Os and ^{189}Os Neutron-Capture Spectra. (A. Stolovy* and B. L. Berman)

The results of this LLL-NRL collaboration will be presented at the 1976 Washington APS Meeting; a paper on this work has been submitted to Phys. Rev. C as well. The APS abstract follows:

"The Spin states of 25 resonances for ^{187}Os and 40 resonances for ^{189}Os have been determined with probabilities of correctness exceeding 85%. These measurements are far superior to previous data¹⁰ taken with much smaller samples. The spin distribution for the ^{187}Os case is needed for the determination of the age of the universe which makes use of the ^{187}Re - ^{187}Os radioactive dating technique. The experiments were performed at the Livermore Linac, using two Ge(Li) detectors and a two-parameter data-collection system. Spin assignments were made on the basis of the ratio of low-energy capture γ -ray intensities depopulating 4^+ states to those of γ rays from 2^+ states. For both isotopes, the spin distribution is consistent with a $(2J+1)$ level-density distribution. The level spacings were found to be in agreement with the theory of Dyson and Mehta,¹¹ which implies the presence of long-range ordering."

4. Neutron Total Cross Section for Tritium. (T. W. Phillips, B. L. Berman, W. A. Barletta, J. D. Seagrave[†])

The results of this LLL-LASL collaboration will be presented at the 1976 Washington APS Meeting. The abstract follows:

¹⁰A. I. Namenson, A. Stolovy, and G. L. Smith, Nucl. Phys. A237, 45 (1975).

¹¹F. J. Dyson and M. L. Mehta, J. Math. Phys. 4, 701 (1963).

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"Using the LLL 100-MeV Linac, we have acquired neutron-transmission data for tritium and hydrogen samples in the neutron energy range from 50 keV to 50 MeV. The 200,000-Ci high-pressure tritium sample, the equivalent hydrogen sample and an evacuated sample container were cycled alternately into the neutron beam along a 250-m flight path. These data have been analyzed to obtain the neutron total cross section for ^3H . That part of the present results which lies within the appropriate energy range is in reasonable agreement with the results of the only previous measurement of this cross section.¹²"

5. Photonuclear Reactions.

(a) Photoneutron Cross Sections for ^{13}C , ^{17}O , and ^{18}O .

A collaborative series of experiments on these cross sections has been performed at the LLL and Toronto linacs. The ground-state photoneutron cross section for ^{17}O was performed at Toronto; ^{13}C , ^{17}O and ^{18}O photoneutron measurements were made at Livermore. Fig. D-2 shows the photoneutron cross sections for ^{18}O . Some of these results were reported at the 1976 New York APS meeting. The abstracts for the work performed at Livermore follow:

"Photoneutron Cross Sections for ^{13}C .[†] K. G. McNEILL and J. G. WOODWORTH, U. of Toronto, J. W. JURY, Trent U., and P. MEYER, D. D. FAUL, and B. L. BERMAN, Lawrence Livermore Lab.--The (γ, n) and $(\gamma, 2n)$ cross sections for ^{13}C have been measured from 7.5 to 42 MeV, using monoenergetic photons from the annihilation in flight of fast positrons from the Livermore Electron-Positron Linac. The photon energy resolution ranged from 300 to 450 keV, and data were acquired at 125-keV intervals below 25 MeV. The photoneutrons were detected in a ~40%-efficient BF_3 -tube-plus-paraffin 4π neutron detector. The sample consisted of 46g of pressed elemental carbon enriched to 96% in ^{13}C . Peaks in the (γ, n) cross section occur at 7.8, 8.2, 11.0, 13.6, and 14.9 MeV. The main giant resonance is centered at 23 MeV. The $(\gamma, 2n)$ cross section rises slowly from threshold and remains small throughout the energy range measured."

[†]Work supported in part by the U.S. Energy Research and Development Administration and the National Research Council of Canada.

¹²Los Alamos Physics and Cryogenics group, Nucl. Phys. 12, 291 (1959).

Fig. D-2. Photonutron cross sections for ^{18}O . (a) Total photonutron cross section $\sigma[(\gamma, n) + (\gamma, pn) + (\gamma, 2n)]$. (b) Photonutron cross section $\sigma[(\gamma, n) + (\gamma, pn)]$. (c) $\sigma(\gamma, 2n)$.

"Photoneutron Cross Section for ^{17}O . P. MEYER, D. D. FAUL, and B. L. BERMAN, Lawrence Livermore Lab., J. W. JURY, Trent U., and J. G. WOODWORTH and K. G. McNEILL, U. of Toronto--The (γ, n) cross section for ^{17}O has been measured from 7.6 to 30 MeV at the Livermore Electron-Positron Linac (under the same conditions as the work on ^{13}C , above.). The sample consisted of 102g of H_2O enriched to 30% in ^{17}O , with most of the balance of the oxygen as ^{18}O . Sequential measurements using a sample of H_2^{18}O (96.5% pure) allowed the subtraction of the neutron counts from the ^{18}O impurity. Additional sequential measurements with samples of H_2^{16}O and D_2^{16}O (at somewhat larger energy intervals) served as a check on the experimental normalization. A broad giant resonance centered at about 23 MeV dominates the $^{17}\text{O}(\gamma, n)$ cross section. The $^{17}\text{O}(\gamma, 2n)$ cross section is very small and difficult to measure in the face of the large $(\gamma, 2n)$ cross section for ^{18}O (see next abstract)."

"Photoneutron Cross Sections for ^{18}O . D. D. FAUL, B. L. BERMAN, P. MEYER, and R. A. ALVAREZ, Lawrence Livermore Lab. and J. G. WOODWORTH, U. of Toronto--The (γ, n) and $(\gamma, 2n)$ cross sections for ^{18}O have been measured from threshold to 42 MeV at the Livermore Electron-Positron Linac (under similar conditions to those for the work on ^{13}C , above). The samples used consisted of 34- and 120-g quantities of H_2O enriched to 96.5% in ^{18}O . Many peaks appear in both the (γ, n) and $(\gamma, 2n)$ cross sections; the most prominent of these occur at 10.1, 11.3, 12.9, 13.7, 14.6, and 15.6 MeV. The main giant resonance is centered at 23.4 MeV. The $(\gamma, 2n)$ cross section rises sharply from threshold, contains prominent structure, and remains large throughout the energy range measured."

(b) Photoproton Cross Sections for ^{18}O : A Measure of the Effect of the Valence Neutrons on the ^{16}O Core.

A report of this work also was given at the 1976 New York A.P.S. meeting, and a paper has been prepared for submittal to Phys. Rev. Letters. Fig. D-3 shows the striking similarities and differences between the ^{18}O and ^{16}O cross sections. The A.P.S. abstract follows:

"Photoproton Cross Section for ^{18}O . B. L. BERMAN, D. D. FAUL, R. A. ALVAREZ, and P. MEYER, Lawrence Livermore Lab.--The (γ, p) cross section for ^{18}O has been measured from threshold to 42 MeV, at the Livermore Electron-Positron Linac, simultaneously with the photoneutron cross sections by detecting (between beam bursts) the delayed

Fig. D-3. (a) Photoproton cross section for ^{18}O measured in this experiment. (b) and (c) Photoproton and photo-neutron cross sections for ^{16}O taken from the literature.

neutrons from the β -decay of the residual ^{17}N nuclei to neutron-unstable states in ^{17}O . The $^{18}\text{O}(\gamma, p)$ cross section contains prominent peaks at 17.3, 19.2, 20.8, and 23.4 MeV, as well as a broad peak centered at ~ 27 MeV. This cross section will be compared and contrasted with the $^{16}\text{O}(\gamma, p)$ cross section (synthesized from published data) in order to demonstrate the dramatic effect of the two valence neutrons in ^{18}O upon the ^{16}O core."

(c) Isospin Shift of the Giant-Resonance Energy.

The results of this LLL-LASL-NBS collaboration will be presented at the 1976 Washington A.P.S. meeting. The abstract follows:

"Isospin Shift of Giant-Resonance Energy. B. L. BERMAN, Lawrence Livermore Laboratory, B. F. GIBSON, Los Alamos Laboratory, and J. S. O'CONNELL, National Bureau of Standards and ERDA.--An examination of the giant-resonance energy derived from Lorentz-curve fits¹³ to photoabsorption cross sections of spherical nuclei ($A \geq 90$) reveals an isotope shift larger in magnitude than the general A -dependence of the resonance energy. These data imply an isospin dependence of the giant-resonance energy. Theoretical models of the electric dipole resonance and isospin sum rules are examined to account for this phenomenon."

(d) Photoneutron Cross Sections for Osmium Isotopes.

The results of these measurements will be presented at the 1976 Quebec A.P.S. meeting. The abstract follows:

"Photoneutron Cross Sections for Osmium Isotopes. (B. L. BERMAN, R. A. ALVAREZ, D. D. FAUL, and P. MEYER, Lawrence Livermore Lab.--We have measured the photoneutron cross sections for $^{188}, ^{189}, ^{190}, ^{192}\text{Os}$ from the (γ, n) threshold to 30 MeV and for ^{186}Os from 11 to 19 MeV, using monoenergetic photons from the annihilation in flight of fast positrons from the LLL Electron-Positron Linac. The photon energy resolution ranged from 300 to 400 keV over the energy range of the experiment. Isotopically enriched powdered-metal osmium samples were used. The objective of this experiment was to test the recent theoretical prediction¹⁴ of a nuclear phase transition, from

¹³B. L. Berman, Atomic Data and Nuclear Data Tables 15, 319 (1975).

¹⁴R. Sedlmayr, M. Sedlmayr, and W. Greiner, Nucl. Phys. A232, 465 (1974).

prolate deformed to γ -unstable between the $1880s$ and $1900s$ nuclei. Values for integrated cross sections and branching ratios for multiple-neutron-emission cross sections were obtained as well."

E. FACILITIES

1. Photoneutron Angular Distribution Facility. (T. W. Phillips)

A facility for the study of the angular distribution and energy spectra of photoneutrons has been installed at the LLL 100 MeV electron linear accelerator. Five angles have been instrumented with neutron detectors. The angles are 22.5° , 67.5° , 90° , 112.5° , and 135° . Neutron spectra are obtained by measuring their time of flight along a 10 m flight path at each angle. Using these flight paths and a 5 nsec electron beam burst width gives an energy resolution of 400 keV for 10 MeV neutrons and 14 keV for 1 MeV neutrons.

As a test of the facility, the angular distribution of photoneutrons from ^{16}O leaving ^{15}O in its ground state is being measured using bremsstrahlung photons. These data are currently being analyzed. The positron converter on the LLL Linac is being upgraded to provide a more intense beam. When this upgrade is complete, annihilation photons will also be used in photoneutron studies. The combination of monoenergetic annihilation photons and time-of-flight spectrometry will make it possible to identify and to study all neutron decay modes of a nucleus excited by photons.

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