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LUCAS HEIGHTS

# THE A.A.E.C. NUCLEAR DATA CARD LIBRARY

by

G. DOHERTY

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## ABSTRACT

This report describes the compilation of the A.A.E.C. nuclear data card library and the conventions relating to the use of the data in neutronics calculations. Details of data processing programmes, library formats, and the extent of the information available for each nuclide are given in the appendices.

## CONTENTS


| | Page |
|---|---|
| 1. INTRODUCTION | 1 |
| 2. SLOWING DOWN THEORY | 1 |
| 3. INELASTIC REACTIONS | 2 |
| 4. CROSS SECTION REPRESENTATION | 2 |
| 5. REFERENCES | 3 |

APPENDIX 1 Programmes Available for Data Processing

APPENDIX 2 Data Library Information

APPENDIX 3 Data Present in the Nuclear Data Card Library December, 1963

## 1. INTRODUCTION

The A.A.E.C. Research Establishment has established a nuclear data card library to provide information for a variety of reactions and nuclides for use in neutronics calculations. The trend towards sophisticated multigroup reactor survey codes involves a considerable increase in data processing. In particular the preparation of basic data in standard format and the adequate documentation of this data is a task of some magnitude.

This report contains a list of the data available for each nuclide and a summary of the methods employed in the preparation and use of the library. Further additions will be published periodically or at the time of any major alteration in library facilities. The library is in card form and conversion to magnetic tape has been delayed until a larger computer is installed at Lucas Heights.

The major function of the library at present is to provide data for the MULGA series of multigroup cross section codes (Clancy et al. 1963) and the bare homogeneous reactor code SKATE (Lawrence 1963). Additions to the library and development of techniques for treating various reactions are mainly governed by the requirements of these codes although the data are of wider application.

## 2. SLOWING DOWN THEORY

In well-moderated reactor systems elastic scattering is the principal mechanism available for the energy degradation of neutrons. A Legendre polynomial analysis of the differential scattering cross section has been used to calculate the slowing down parameters at various lethargy values for both moderator and fuel nuclides.

Defining $\mu = \cos\theta$ where $\theta$ is the angle in the centre-of-mass system, the differential elastic scattering probability function is denoted $g(\mu)$ where:

$$\int_{-1}^{+1} g(\mu)\, d\mu = 1 \ .$$

Following Keane and Pollard (1962), define:

$$K(p) = \int_{-1}^{+1} [1 - \delta(1-\mu)]^{p}\, g(\mu)\, d\mu \ ,$$

where $\delta = \frac{1}{2}(1-\alpha)$ and $(1-\alpha)$ is the maximum fractional energy loss on collision. The average logarithmic energy decrement $\xi$ and the Greuling-Goertzel coefficient $\gamma_0$ are then given by:

$$\xi = -K'(0)$$

$$\gamma_0 = \frac{K''(0)}{2(K'(0))^2} \ ,$$

where

$$K^{(n)}(0) = \int_{-1}^{+1} [\ln\{1 - \delta(1-\mu)\}]^{n}\, g(\mu)\, d\mu \ .$$

The differential elastic scattering probability has been evaluated as a seven-term Legendre polynomial expansion for Be, O, and C by Joanou et al. (1961) at various lethargy points. It was decided that Legendre polynomial expansions would provide the most tractable representation of $g(\mu)$ because interpolation in the six coefficients defines the entire distribution $-1$ to $+1$, at the same time retaining the normalization condition.

Point by point $g(\mu)$ tabulations were available (Buckingham et al. 1960) and a programme was written to transform the tabulation into the Legendre polynomial coefficient form. The extensive compilation of Goldberg et al. (1962) is now available for the calculation of slowing down parameters for a large range of heavy and intermediate nuclides. The one programme RPX047 (Appendix 1) processes directly from pointwise $g(\mu)$ tabulations into slowing down parameters, with Legendre polynomial coefficients as optional intermediate output.

## 3. INELASTIC SCATTERING REACTIONS

An attempt has been made to treat inelastic scattering reactions as an absorption with subsequent re-emission in a standard spectrum. This simplification has been applied only for heavy nuclides where the large number of levels precludes the possibility of calculating excitation probabilities for individual levels.

A typical MULGA 1 Spectrum (Clancy et.al. 1963) was used to calculate the spectrum of inelastically scattered neutrons using the secondary energy laws of Buckingham et al. (1960). The emission spectrum was renormalized to unit reaction rate allowing inelastic scattering to be treated in the same manner as the fission reaction. The use of the inelastic scattering spectrum is confined at present to the MULGA codes for which the simplified treatment is adequate.

The representation of absorption and re-emission is limited in accuracy by the difference between the incident spectrum of the problem and the typical spectrum used to establish the standard re-emission spectrum. The rather nominal secondary energy laws used in the calculation are also a severe limitation on the accuracy afforded by this representation. For well-moderated systems, the inelastic scattering reaction in the fuel is of minor importance and the typical energy spectrum at high energy is reasonably independent of fuel concentration. Systems for which inelastic scattering is a major reaction will require a more sophisticated approach involving scattering cross sections from individual levels which may then be accurately included in the energy degradation process. The liquid drop model of inelastic scattering will provide an alternative approach when the number of levels becomes too large to treat each individually.

The (n,2n) reaction in beryllium has been treated as a negative absorption which produces an additional neutron for each reaction. Following emission, the two neutrons are included in the group-to-group scattering cross sections according to the standard Be (n,2n) spectrum of the library, prepared by Keane and Mills (1962). The use of a standard (n,2n) emission spectrum is not subject to the same deficiencies as those involved in the similar treatment of the (n,n') reaction. This is due to the fact that the systems under consideration are moderated by BeO which predominates to such an extent that the high energy typical spectrum is preserved.

## 4. CROSS SECTION REPRESENTATION

The cross sections of heavy nuclides have sharp low energy resonance peaks which do not lend themselves to treatment as a continuous cross section curve. In the region away from a resonance, the cross section and flux are slowly varying and the flux equation can be solved using relatively few points. Near a resonance the flux and cross section are rapidly varying and many points must be taken to represent the resonance adequately in the flux equation.

The resonance shapes are temperature dependent both in peak height and in the width of the resonance, requiring a new tabulation for each new temperature to be surveyed. The enormous task of preparing the data at various temperatures and the time involved in calculating the flux across a large number of points suggest that a resonance parameter representation will prove more profitable in flux calculations.

For nuclides which have resonance separations much larger than the resonance widths, the Breit-Wigner single level approximation appears to be adequate:

$$\sigma_{n,\gamma} = \frac{6.502 \times 10^5\ \Gamma_n\ \Gamma_\gamma}{E_o} \sqrt{\frac{E_o}{E}}\ \frac{1}{(E-E_o)^2 + \Gamma^2/4} ,$$

where $\Gamma_n$, $\Gamma_\gamma$, and $\Gamma$ are the scattering, absorption, and total widths respectively, of a resonance with central energy $E_o$. In fact for resonances above about 5 eV, the $\sqrt{E_o/E}$ may be neglected in the resonance where the term $(E - E_o)^2 + \Gamma^2/4$ is more rapidly varying. Between resonances, the factor $\sqrt{E_o/E}$ regains its importance but the cross section has become small under the influence of the denominator term.

Much effort has been expended on the calculation of resonance absorption, neglecting the $\sqrt{E_0/E}$ term, and on the temperature dependence of the absorption. It was therefore decided that the most acceptable representation would be a combination of resonance parameters and a temperature independent background cross section which does not have the rapid variation of the original resonance shape. The absorption of a resonance is included in flux calculations as a discontinuity in slowing down density at the central energy of the resonance, the slowing down density being reduced by the resonance escape probability. The resonance absorption can thus be evaluated at any temperature using one of the conventional approximations, and only the temperature dependence of the background cross section is neglected.

Using the approximation outlined in the preceding paragraph, the cross section can be adequately represented both in the resonance and well-removed from the resonance. There appears to be a departure from the theoretical shape in the wings of some resonances which may be due to instrumental beam resolution or to the inadequacy of the single level approximation. The discrepancy is particularly apparent in the region of the Pu 240 resonance at 1 eV, which should be a suitable subject for a more detailed investigation.

The fissile isotopes pose a more complicated problem in that the level spacings are too small to justify the use of the single level approximation and the fission widths are quite large. In the Bohr model, fission proceeds through a limited number of deformed compound nucleus states of different spin and parity. Because of the small number of reaction channels, the model explains the interference of neighbouring fission resonances which is evident, particularly in U233. We are faced with the problem of prescribing a background cross section which must be slowly varying and temperature independent and which combines with the symmetric single level approximation preserving reaction rates.

The cross section in the region $10^{-3}$ to 1 eV can be represented using negative energy resonances which correspond to the compound nucleus decay channels that are energetically impossible. Unfortunately the interfering resonance shapes above 1 eV are beyond the scope of a single level fit and further analysis is required to decide a suitable representation for fission resonances.

A resonance integral programme was written to check the resonance parameters of the library against experimentally measured integrals but the insensitivity of the calculation to all but the leading resonance, and the uncertainties in the experimental results, preclude any detailed check. The programme may be able to provide a rough guide to the spectrum used in measuring the integral of a calibrating material such as gold.

## 5. REFERENCES


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Buckingham, B.R.S., Parker, K., and Pendlebury, E.D. (1960). - Neutron cross sections of selected elements and isotopes for use in neutronics calculations in the energy range 0.025 eV - 15 MeV. AWRE 0-28/60.

Clancy, B.E., Doherty, G., Keane, A., Kletzmayer, Miss E., and Pollard, J.P. (1963). - MULGA - A complex of codes for the determination of multigroup averaged cross section data. AAEC/E114.

Diven, B.C., and Hopkins, J.C. (1961). - Number of prompt neutrons per fission for U233, U235, Pu239, and Cf252. Proc. I.A.E.A. Conf. on Physics of Fast and Intermediate Reactors, Vienna.

Garrison, J.D., and Roos, B.W. (1962). - Fission-product capture cross sections. Nuclear Science and Engineering 12 (1): 115.

Goldberg, M.D., May, V.M., and Stehn, J.R. (1962). - Angular distributions in neutron induced reactions. Vol 1, Z = 1 to 22; Vol 2, Z = 23 to 94. BNL400-TID4500.

Hughes, D.J., and Schwartz, R.B. (1956). - Neutron Cross Sections BNL 325.

Hughes, D.J., Magumo, B.A., and Brussel, M.K. (1960). - Neutron Cross Sections. BNL325 Supplement 1.

Joanou, G.D., Goodjohn, A.J., and Wikner, N.F. (1961). - Legendre expansion coefficients for the angular distribution of elastically scattered neutrons and fast neutron cross sections for deuterium, beryllium, carbon, oxygen, zirconium, lead, and bismuth. GA1256.

Lawrence, B.R. (1963). - A basis for the computation of the energy dependence of the neutron flux and slowing down density in a bare reactor. AAEC/E111.

Keane, A., and Mills, R.G. (1962). - High energy neutron spectra in infinite homogeneous reactor systems moderated by beryllium or beryllia. AAEC/E 91.

Keane, A., and Pollard, J.P. (1962). - Slowing down with anisotropic scattering. Nuclear Science and Engineering 12 (2): 313.

Parker, J.B., and Parker, K. (1960). - The preparation of nuclear data for use in neutronics calculations on high speed computers. AWRE 0-20/60.

# APPENDIX 1

## PROGRAMMES AVAILABLE FOR DATA PROCESSING

RPD006

A resonance integral programme which calculates the infinitely dilute resonance integral in a spectrum $E^{\alpha-1}$ between any assigned energy limits. The programme may be used to calculate negative energy resonance parameters, average resonance parameters for the unresolved region, and also estimated resonance parameters for specified level spacing in the unresolved region. The effect of negative energy resonances, $l > 0$ orbital reactions, and the statistical scattering width fluctuation are included in the resonance integral.

RPD008

A single level Breit-Wigner cross section generating programme useful for comparing resonance parameter representations with experimental cross sections. Resonances may be included or removed with or without the $\sqrt{E_0/E}$ factor which contributes to the thermal cross section. The main use of the programme is to prepare background cross sections which may be used in conjunction with resonance parameters to represent cross sections in flux calculations.

RP039

A general least squares programme has been written to produce least square fits of any data to proposed curves. Exponential functions cannot be attempted except in the log-linear transformation as the programme uses an iterative Taylor series expansion which is not convergent for exponential type functions.

NDCCC1

Library preparation programme which processes library cards into cross section data at 0.1 lethargy intervals and stores the interpolated data in collapsed format on magnetic tape. MULGA and SKATE tapes are compatible with the output library tape.

NDCCC2

Tape editing programme which may be used to compile MULGA tapes from NDCCC1 tapes; NDCCC1 tapes from MULGA tapes; SKATE tapes from NDCCC1 tapes; or to merge existing MULGA tapes.

RPX047

Programme to produce slowing down parameters in the required data library format. Input may be differential scattering cross sections or Legendre polynomial expansion coefficients of the probability function $g(\mu)$. If differential cross sections are supplied, the Legendre expansion coefficients are produced as intermediate output.

## APPENDIX 2

### DATA LIBRARY INFORMATION

| Information | Indicative | Code Number |
|---|---|---|
| Total cross section | NTO | bb1 |
| Elastic scattering cross section | NNE | bb2 |
| Absorption cross section (total – elastic) | NAB | bb3 |
| Inelastic scattering cross section | NNI | bb4 |
| (n,2n) cross section | N2N | bb5 |
| (n,3n) cross section | N3N | bb6 |
| Fission cross section | NF | bb7 |
| Radiative capture cross section | NG | bb8 |
| (n,p) cross section | NP | bb9 |
| (n,d) cross section | ND | b10 |
| (n,t) cross section | NT | b11 |
| (n,He3) cross section | NH3 | b12 |
| (n, $\alpha$) cross section | NA | b13 |
| (n,2 $\alpha$) cross section | N2A | b14 |
| Neutron removal cross section | NC | b15 |
| Resolved resonance parameters | RRP | b17 |
| Average resonance parameters | URP | b18 |
| $\bar{\nu}$ (fission) | NU | b33 |
| (n,n') emission spectrum | NSI | b52 |
| (n,2n) emission spectrum | NSN | b53 |
| (n,f) emission spectrum | NSF | b55 |
| Slowing down parameters | SDP | b60 |
| Coeffs. $g_1$, $g_2$, $g_3$ of diff. scatt. prob. | LPC | b61 |
| Coeffs. $g_4$, $g_5$, $g_6$ of diff. scatt. prob. | LPC | b62 |

The indicative and code number assignments are substantially those of Parker and Parker (1960).

All library information is identified in columns 63 – 80 where the following items are punched:

| | | |
|---|---|---|
| columns | 63 – 65 | code number |
| | 67 – 68 | proton number |
| | 70 – 72 | mass number |
| | 73 – 75 | indicative |
| | 76 – 77 | chemical symbol |
| | 78 – 80 | mass number. |

(continued)

**APPENDIX 2** (continued)

Cross section sets contain lethargy u, (10 MeV zero), energy E, (MeV), and cross section $\sigma$ in barns. Resolved resonance information consists of lethargy u, central resonance energy $E_o$ (eV), neutron scattering width $\Gamma_n$, radiative capture width $\Gamma_\gamma$, fission width $\Gamma_f$, and statistical spin factor g(J). Unresolved resonance data contains the lethargy $u_L$ of the last resolved resonance, the average level spacing D(eV), the average reduced neutron scattering width $\overline{\Gamma_n^o}$ ( = $\Gamma_n/\sqrt{E}$ ), the average radiative capture width $\overline{\Gamma_\gamma}$, the average fission width $\overline{\Gamma_f}$, and the average spin factor $\overline{g(J)}$, reflecting the preponderance of a particular spin state. Spectrum information consists of lethargy, energy (MeV), source per unit lethargy S(u), source per unit energy S(E) ( = S(u)/E), and integrated lethargy source $\int S(u)\,du$. Slowing down parameter data are lethargy, energy (MeV), the average logarithmic energy decrement $\xi$, the Greuling–Goertzel coefficient $\gamma_o$, the second order correction term $\gamma_1$, and the average laboratory angle cosine $\overline{\mu}$. The differential scattering probability is represented by $g_1$, $g_2$, $g_3$, $g_4$, $g_5$, and $g_6$, the first six non-trivial Legendre polynomial expansion coefficients ($g_o$ = 1).

The following is a list of formats in which the various types of data are punched. All cards are identified in the manner indicated above.

| Type of data | Format |
|---|---|
| cross sections | (F7.3, 1P 2 E 11.3) |
| resonance parameters (resolved and average) | (F7.3, 1P E 11.3, 4 E 10.2) |
| $\overline{\nu}$ curves | (F7.3, 1P 2 E 11.3) |
| spectra | (F7.3, 1P 4 E 11.3) |
| slowing down parameters | (F7.3, 1P 5 E 11.3) |
| u, E, $g_1$, $g_2$, $g_3$ | (F7.3, 1 P 4 E 11.3) |
| u, E, $g_4$, $g_5$, $g_6$ | (F7.3, 1P 4 E 11.3) |

## APPENDIX 3

## DATA PRESENT IN THE NUCLEAR DATA CARD LIBRARY DECEMBER, 1963

Note: Reference AWRE is Buckingham et al. (1960).
BNL325 is Hughes and Schwartz (1956) and Hughes et al. (1960).
BNL400 is Goldberg et al. (1962).
GA2156 is Joanou et al. (1961).
RPX047 refer Appendix 1 for programme description.
RPD008 refer Appendix 1 for programme description.
RPD006 refer Appendix 1 for programme description.

| Nuclide | Data | Source | Comments |
|---|---|---|---|
| $_1H^2$ | NTO | AWRE | Tabulated to 1.E−9 MeV. |
| | NNE | AWRE | Tabulated to 1.E−9 MeV. |
| | N2N | AWRE | Threshold about 3.3 MeV. |
| $_1H^3$ | NTO | AWRE | Tabulation to 2.5 E−8 MeV. |
| | NNE | AWRE | Tabulation to 2.5 E−8 MeV. |
| | NAB | AWRE | Threshold about 8.3 MeV. |
| | N2N | AWRE | Threshold about 8.3 MeV. |
| | N3N | AWRE | Threshold about 11 MeV. |
| $_2He^3$ | NTO | AWRE | Tabulation to 2.5 E−8 MeV. |
| | NNE | AWRE | Tabulation to 2.5 E−8 MeV. |
| | NAB | AWRE | Tabulation to 2.5 E−8 MeV. |
| | N2N | AWRE | Threshold about 10 MeV. |
| | NP | AWRE | Tabulation to 2.5 E−8 MeV. |
| | ND | AWRE | Threshold about 4 MeV. |
| $_2He^4$ | NTO | AWRE | Tabulation to 2.5 E−8 MeV. |
| $_3Li^6$ | NTO | AWRE | Tabulation to 3.E−9 MeV. |
| | NNE | AWRE | Tabulation to 3.E−9 MeV. |
| | NA | AWRE | Tabulation to 3.E−9 MeV. |
| $_4Be^9$ | NTO | AWRE | Tabulation to 2.5 E−8 MeV. |
| | NNE | AWRE | Tabulation to 2.5 E−8 MeV. Taken as constant below this energy and tabulation extended to 1.E−9 MeV. |
| | NAB | AWRE | Tabulation to 2.5 E−8 MeV. Cross section assumed 1/v below this energy and tabulation extended to 1.E−9 MeV. |
| | N2N | AWRE | Threshold about 1.5 MeV. |
| | NA | AWRE | Threshold about 1 MeV. |
| | NG | AWRE | Tabulation to 2.5 E−8 MeV. |
| | NT | AWRE | Threshold about 11 MeV. |
| | NSN | Keane and Mills (1962) | (n,2n) emission spectrum for Be mixtures. |
| | NSN | Keane and Mills (1962) | (n,2n) emission spectrum for BeO mixtures. |
| | LPC | GA2156 | Some high energy Legendre expansions renormalized to remove negative values introduced by inadequacy of 7 polynomial fit. |
| | SDP | RPX047 | (Using LPC). |

(continued)

## APPENDIX 3 (continued)

| Nuclide | Data | Source | Comments |
|---|---|---|---|
| $_5B^{10}$ | NNE | BNL325 | Tabulation taken to 1.E MeV on the assumption of constant cross section. |
| | NNI | BNL325 | Threshold about 2.25 MeV. |
| | NG | BNL325 | Tabulation taken to 1.E-9 MeV assuming 1/v cross section variation. |
| | LPC | RPX047 | Analysis of differential scattering data from BNL 400. |
| | SDP | RPX047 | (Using LPC). |
| $_5B^{NAT}$ | NTO | AWRE | Tabulation to 1.E-9 MeV assuming elastic constant, absorption 1/v. |
| | NNE | AWRE | Tabulation to 1.E-9. |
| | NAB | AWRE | Tabulation to 1.E-9. |
| $_6C^{12}$ | NTO | AWRE | Lower energy limit 2.5 E-8 MeV. |
| | NNE | AWRE | Lower energy limit 2.5 E-8 MeV. The tabulation has been extended to 1.E-9 MeV assuming constant cross section. |
| | NNB | AWRE | Lower energy limit 2.5 E-8 MeV. Assuming 1/v cross section variation the tabulation has been extended to 1.E-9 MeV. |
| | NNI | AWRE | Threshold reaction lower energy limit about 4.8 MeV. |
| | NG | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NP | AWRE | Threshold reaction. Lower energy limit about 14 MeV. |
| | NA | AWRE | Threshold reaction. Lower energy limit about 7 MeV. |
| | LPC | GA2156 | Occasional renormalization required for high energy expansions. |
| | SDP | RPX047 | |
| $_8O^{16}$ | NTO | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NNE | AWRE | Tabulation to 2.5 E-8 MeV extended to 1.E-9 MeV assuming constant scattering. |
| | NAB | AWRE | Tabulation to 2.5 E-8 MeV extended to 1.E-9 MeV assuming 1/v cross section variation. |
| | NNI | AWRE | Threshold 6 MeV. |
| | NP | AWRE | Threshold 10 MeV. |
| | ND | AWRE | Threshold 10 MeV. |
| | NA | AWRE | Threshold 3.5 MeV. |
| | LPC | GA2156 | Some high energy expansions renormalized. |
| | SDP | RPX047 | (Using LPC) |
| $_{13}Al^{27}$ | NTO | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NNE | AWRE | Tabulation to 2.5 E-8 MeV. The variation in cross section below 10 eV has been discarded and a constant 1.41 barns has been assumed to 1.E-9 MeV. |
| | NAB | AWRE | Tabulation to 2.5 E-8 MeV extended to 1.E-9 assuming 1/v behaviour. |
| | NNI | AWRE | Threshold about 0.5 MeV. |
| | NG | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NP | AWRE | Threshold about 2 MeV. |
| | ND | AWRE | Threshold about 6.5 MeV. |
| | NA | AWRE | Threshold about 3.5 MeV. |
| | LPC | RPX047 | Differential scattering data from BNL400. |
| | SDP | RPX047 | (Using LPC). |

(continued)

**APPENDIX 3 (continued)**

| Nuclide | Data | Source | Comments |
|---|---|---|---|
| $_{14}Sc^{28}$ | NTO | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NNE | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NAB | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NNI | AWRE | Threshold about 1.7 MeV. |
| | NG | AWRE | Lower energy tabulation 2.5 E-8 MeV. Upper energy tabulation 6.E-4 MeV. |
| $_{24}Cr^{NAT}$ | NTO | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NNE | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NAB | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NNI | AWRE | Threshold about 1.4 MeV. |
| | NG | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NP | AWRE | Threshold about 5.5 MeV. |
| | NA | AWRE | Threshold about 5.5 MeV. |
| $_{25}Mn^{55}$ | NNE | BNL325 | Lower energy tabulation 1.E-9 MeV. |
| | NG | BNL325 | Above resonances; RPD008 used to generate cross section through resonances to 1.E-9 MeV. |
| $_{26}Fe^{NAT}$ | NTO | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NNE | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NAB | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NNI | AWRE | Threshold about 0.85 MeV. |
| | N2N | AWRE | Threshold about 11 MeV. |
| | NG | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NP | AWRE | Threshold about 2.5 MeV. |
| | NA | AWRE | Threshold about 10 MeV. |
| | LPC | RPX047 | Differential scattering data from BNL 400. |
| | SDP | RPX047 | (Using LPC). |
| $_{28}Ni^{NAT}$ | NTO | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NNE | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NAB | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NNI | AWRE | Threshold about 1 MeV. |
| | N2N | AWRE | Threshold about 11 MeV. |
| | NG | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NP | AWRE | Threshold about 3 MeV. |
| | NA | AWRE | Threshold about 5 MeV. |
| $_{48}Cd^{NAT}$ | NTO | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NNE | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NAB | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NNI | AWRE | Threshold about 0.4 MeV. |
| | N2N | AWRE | Threshold about 7 MeV. |
| | NG | AWRE | Tabulation to 2.5 E-8 MeV. |
| $_{49}In^{115}$ | NNE | BNL325 | Tabulation to 1.E-9 on assumption of constant cross section. |
| | NG | BNL325 | Above resonances; RPD008 used to generate cross section through resonance region and down to 1.E-9 MeV. |

(continued)

## APPENDIX 3 (continued)

| Nuclide | Data | Source | Comments |
|---|---|---|---|
| $_{90}Th^{232}$ | NTO | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NNE | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NAB | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NAB | RPD008(1) | Calculated from resonance parameters. Background cross section 2.5 E-8 MeV to 1.E-3 MeV. |
| | NAB | RPD008(2) | Background cross section for use in MULGA. Lower energy tabulation 1.E-9 MeV, Upper energy 4.54 E-4 MeV. |
| | NNI | AWRE | Threshold about 0.045 MeV. |
| | N2N | AWRE | Threshold about 6 MeV. |
| | N3N | AWRE | Threshold about 11 MeV. |
| | NF | AWRE | Threshold about 1 MeV. |
| | NG | AWRE | As for NAB (AWRE). |
| | NG | RPD008(1) | As for NAB (RPD008(1)). |
| | NG | RPD008(2) | As for NAB (RPD008(2)) |
| | LPC | RPX047 | Differential scattering data from AWRE, BNL 400. |
| | SDP | RPX047 | (using LPC). |
| | NU | AWRE | Generated using parameters of AWRE. |
| | RRP | BNL 325 | Resonances resolved up to 1000 eV are included in the library negative energy resonance calculated RPD006. |
| $_{92}U^{233}$ | NTO | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NNE | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NAB | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NAB | RPD008(1) | Resolved resonances removed to give background cross section up to 26 eV. |
| | NAB | RPD008(2) | Resonance less than 0.1 eV included in background for MULGA programmes. |
| | NNI | AWRE | Threshold about 4.E-2 MeV. |
| | N2N | AWRE | Threshold about 6 MeV. |
| | N3N | AWRE | Threshold about 13 MeV. |
| | NF | AWRE | As for NAB (AWRE). |
| | NF | RPD008(1) | As for NAB (RPD008(1)). |
| | NF | AWRE | As for NAB (RPD008(2)). |
| | NG | AWRE | As for NAB (AWRE). |
| | NG | RPD008(1) | As for NAB (RPD008(2)). |
| | RRP | BNL325 | Parameters are multi-level and errors arise in their use in single level cross section analysis. Last resolved resonance 25.48 eV. |
| | LPC | RPX047 | Data from AWRE, BNL 400 for differential elastic scattering. |
| | SDP | RPX047 | (using LPC). |
| | NU | | Generated using parameters of Diven and Hopkins (1961). |
| | NSF | ANL5800 | Fission spectrum generated. |
| $_{92}U^{234}$ | RRP | BNL325 | Last resolved resonance 191 eV. |
| | LPC | RPX047 | Data from AWRE, BNL 400. |
| | SDP | RPX047 | (using LPC). |

(continued)

## APPENDIX 3 (continued)

| Nuclide | Data | Source | Comments |
|---|---|---|---|
| $_{92}U^{235}$ | NTO | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NNE | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NAB | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NAB | RPD008(1) | Resolved resonances up to 19.3 eV removed giving background cross section. |
| | NAB | RPD008(2) | Resolved resonances removed up to 67.8 eV. Resonance below 1 eV included for MULGA data. |
| | NNI | AWRE | Threshold 0.013 MeV. |
| | N2N | AWRE | Threshold 5 MeV. |
| | N3N | AWRE | Threshold 12 MeV. |
| | NF | AWRE | As for NAB (AWRE). |
| | NF | RPD008(1) | As for NAB (RPD008(1)). |
| | NF | RPD008(2) | As for NAB (RPD008(2)). |
| | NG | AWRE | As for NAB (AWRE). |
| | NG | RPD008(1) | As for NAB (RPD008(1)). |
| | NG | RPD008(2) | As for NAB (RPD008(2)). |
| | RRP | BNL325 | Resonances from 19.3 to 67.8 eV have been generated using RPD006. |
| | LPC | RPX047 | Differential cross section from BNL 400, AWRE. |
| | SDP | RPX047 | (using LPC). |
| | NU | | Generated from curve of Diven and Hopkins (1961). |
| $_{92}U^{236}$ | NAB | BNL325 | Continuous cross sections above 4.5 E-4 MeV. |
| | | RPD008 | Background cross section generated below 4.5 E-4 MeV. |
| | NNI | BNL325 | Threshold 3.7 E-2 MeV. |
| | NF | | Threshold about 0.25 MeV. |
| | RRP | RPD006 | Negative energy resonance calculated RPD006. |
| | | BNL325 | Resolved resonances up to 450 eV. |
| | LPC | RPX047 | Differential scattering data from AWRE, BNL 400. |
| | SDP | RPX047 | (using LPC). |
| $_{92}U^{238}$ | NTO | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NNE | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NAB | AWRE | Tabulation to 2.5 E-8 MeV. |
| | NAB | RPD008(1) | Background cross section calculated up to 1.E-3 MeV. |
| | NAB | RPD008(2) | Background cross section calculated up to 4.54 E-4 MeV. |
| | NNI | AWRE | Threshold about 4.4 E-2 MeV. |
| | N2N | AWRE | Threshold about 5.5 MeV. |
| | N3N | AWRE | Threshold about 11 MeV. |
| | NF | AWRE | Threshold about 55 MeV. |
| | NG | AWRE | Tabulation to 2.5 E-8 MeV. |
| | RRP | BNL325 | Resonances resolved up to 1.E-3 MeV. |
| | LPC | RPX047 | Differential scattering data from AWRE, BNL 400. |
| | SDP | RPX047 | |
| | NU | AWRE | Generated from AWRE curve. |

(continued)

## APPENDIX 3 (continued)

| Nuclide | Data | Source | Comments |
|---|---|---|---|
| $_{94}Pu^{239}$ | NTO | AWRE | Tabulation to 2.5 E–8 MeV. |
| | NNE | AWRE | Tabulation to 2.5 E–8 MeV. |
| | NAB | AWRE | Tabulation to 2.5 E–8 MeV. |
| | NAB | RPD008(1) | Resonance removed to give background up to 52 eV. |
| | NAB | RPD008(2) | Resonances removed, 0.3 eV resonance included. |
| | NNI | AWRE | Threshold about 8.E–3 MeV. |
| | N2N | AWRE | Threshold about 5.5 MeV. |
| | N3N | AWRE | Threshold about 11 MeV. |
| | NF | AWRE | As for NAB (AWRE). |
| | NF | RPD008(1) | As for NAB (RPD008(1)). |
| | NF | RPD008(2) | As for NAB (RPD008(2)). |
| | NG | AWRE | As for NAB (AWRE). |
| | NG | RPD008(1) | As for NAB (RPD008(1)). |
| | NG | RPD008(2) | As for NAB (RPD008(2)). |
| | LPC | RPX047 | Data from BNL 400, AWRE for differential scattering. |
| | SDP | RPX047 | |
| | RRP | BNL325 | Resonances resolved up to 52.6 eV. Negative energy resonance calculated RPD006. |
| | NU | | Generated from curve of Diven and Hopkins (1961). |
| | NSF | ANL5800 | Generated from proposed curve. |
| $_{94}Pu^{240}$ | NTO | BNL325 | Tabulation to 2.5 E–8 MeV. |
| | NNE | BNL325 | Tabulation to 2.5 E–8 MeV. |
| | NAB | BNL325 | Down to 119 eV. |
| | | RPD008 | Background cross section below this energy. |
| | NNI | BNL325 | Threshold about 7.E–2 MeV. |
| | NG | | As for NAB. |
| | NU | AWRE | Generated from proposed curve. |
| | RRP | BNL325 | Resonances resolved up to 119 eV. |
| | LPC | RPX047 | Differential scattering data RPX047. |
| | SDP | RPX047 | |
| $_{94}Pu^{241}$ | NTO | BNL325 | Tabulation to 1.E–8 MeV. |
| | NNE | BNL325 | Tabulation to 1.E–8 MeV. |
| | NAB | BNL325 | Tabulation to 1.E–8 MeV. |
| | NAB | RPD008 | Resonance at 0.2 eV included in background cross section. |
| | NNI | BNL325 | Threshold 5.E–3 MeV. |
| | NF | BNL325 | As for NAB (BNL). |
| | NF | RPD008 | As for NAB (RPD008). |
| | NG | BNL325 | As for NAB (BNL). |
| | NG | RPD008 | As for NAB (RPD008). |
| | LPC | RPX047 | Differential scattering data from BNL 400, AWRE. |
| | SDP | RPX047 | |
| | RRP | BNL325 | Negative energy resonance calculated RPD006. |
| | NU | Diven and Hopkins (1961) | Generated from proposed curve. |
| | NSF | ANL5800 | Generated from proposed curve. |

(continued)

## APPENDIX 3 (continued)

Capture cross sections for the following fission products have been taken from the tabulation of Garrison and Roos (1962):

Mo95, Te99, Rh103, Cd113, Xe131, Cs133, Xe135, Nd143, Nd145, Pm147, Sm149, Sm151, Sm152, Eu153, Gd155, Gd159.

Resonance parameters for the following nuclides have been taken from BNL 325:

V51, Mn55, Cu63, Zn68, Co59, Br79, Rb87, Y89, Te99, Mo100, Rh103, Ag109, In113, In115, Cs133, Xe131, Xe135, Na139, Nd145, Pm147, Sm149, W186, Au197, Pt198, natural Mo, and natural Hf.