Memo 4C-3/92

To: Distribution — 17 October 1973

From: H.D. Lemmel *HDL*

Subject: Provisional Manual-Pages

Please, find attached some provisional Manual-pages (compare Memo 4C-3/90, page 2, item 4) on Fission-Yields and Fission Neutron Spectra Data. These were taken from INDC(NDS)-51, pages 40-49 and were approved during the 8th 4C-Meeting, October 1972, but never distributed as Manual pages.

The existing LX4 page "Spectrum Average" had to be updated simultaneously.

The absence of this Manual update caused mistakes in our compilation work.

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FIS-SPEC 1)

Fission-Neutron Spectra Data

This subject concerns the following data-types which should be compiled in EXFOR.

1.) energy-spectra of fission neutrons, point-data
2.) fitting-parameters of fission-neutron spectra
3.) fission-neutron spectrum averaged cross-sections

Literature, e.g.: James Terrell: Fission Neutron Spectra and Nuclear Temperature, Phys. Rev. 113, p.527, Jan. 1959.

Prompt Fission Neutron Spectra. 71 VIENNA

A note on incident neutrons: Fission-neutron spectra are dependent on the energy of the incident neutrons. Data are given for "thermal" and "fast" fission. "Thermal" fission spectrum data refer to both: 0.0253 eV neutrons and thermal Maxwellian neutrons; the results are indistinguishable. It is therefore not recommended to use the MXW modifier when incident neutrons are thermal Maxwellian. Also for fission spectrum data induced by fast neutrons (monoenergetic or spectrum average) it is recommended to enter a numerical value for the incident neutron-energy and not to use the modifier FIS. The modifiers MXW, FIS or SPA are not relevant in this case, and the quantity codes are complex enough without. The incident neutron spectrum needs only to be described in free text under INC-SPECT.

1.) For point-data of fission-neutron energy-spectra

the following quantity-codes exist already in dictionary 14 or can be formed in analogy:

NU,DE	energy-spectrum of fission-neutrons, total
NU,DE,PR	energy-spectrum of prompt fission-neutrons
SF/NU,DE	energy-spectrum of spontaneous fission-neutrons, total
SF/NU,DE,PR	energy-spectrum of spontaneous prompt fission-neutrons

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FIS-SPEC 2)

In the literature, these data are usually called $\chi(E)$. Data are mostly given in arbitrary units, which require the REL modifier in the quantity-code. In the normalized form $\int \chi(E)\, dE = 1$ data have the units of a reciprocal energy.

The data are functions of the outgoing-neutron energy E, with the incident neutron-energy EN to be entered under COMMON.

2.) Fission-neutron spectrum data are fitted either to a Maxwellian or to a Watt-spectrum or to one of several other definod spectra.

The Maxwellian spectrum has the shape

$$N(E) \sim \sqrt{E}\, \exp(-E/T)$$

where E is the energy of the fission-neutron and T is the spectrum-temperature given in MeV. Often given are also the average kinetic energy $\bar{E}$ and the most probable energy E_p which are defined as

$$\bar{E} = 3T/2$$

$$E_p = T/2 = \bar{E}/3$$

The Wattspectrum is based on the assumption that fragments emit neutrons with a Maxwellian spectrum in the center-of-mass system. The shape of the Watt spectrum is

$$N(E) \sim \exp(-E/T)\, \sinh\left(\frac{2}{T}\sqrt{EE_f}\right)$$

where T is the spectrum-temperature given in MeV but deviating from the temperature defined in the Maxwellian fit; E_f is a theoretical "fragment kinetic energy per nucleon". The average kinetic energy $\bar{E}$ is defined here as

$$\bar{E} = E_f + 3T/2.$$

The numerical value of $\bar{E}$ should be approximately the same disregarding to which spectrum shape the data were fitted.

Since the average kinetic energy $\bar{E}$ is the only quantity which is comparable in all fits, EXFOR entries should be made for the quantity $\bar{E}$, which should be coded

$$\bar{E} = \text{NU,AKE}.$$

Details of the fit and of the spectrum shape assumed should be given under ANALYSIS; also any further numerical parameters obtained in the fit such as T, E_p or E_f shall be entered here in free text. By this procedure it is avoided that the Watt-spectrum parameters are entered in three different subentries, one each for the quantities $\bar{E}$, T and E_f. When in the case of a Maxwellian fit the author gives only T, the compiler is asked to calculate $\bar{E}$ from $\bar{E} = 3T/2$.

In most cases only the prompt neutrons are considered; the quantity-code is then

NU,AKE,PR

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FIS-SPEC 3)

Data are functions of incident neutron energy EN except in the case of spontaneous fission, where the quantity-code is

SF/NU, AKE, PR

Again, no modifier shall be given to indicate an incident neutron spectrum.

3.) Fission neutron spectrum averaged cross-sections are entered with the modifier FIS. (Note that this modifier was introduced only at the end of 1972; data compiled earlier were coded with the more general modifier SPA.) This is to be combined with an entry under EN-DUMMY. The numerical value under EN-DUMMY should be the temperature $T = 2/3\ \bar{E}$ of the given spectrum, or 1.5 MeV if T is not known.

It must be evident in the EXFOR-entry

* whether data were measured directly and in what kind of spectrum (free text under METHOD and INC-SPECT)
* or whether data were calculated by integrating a measured cross-section curve over an assumed fission-neutron spectrum (free text under ANALYSIS).

In the first case it should be specified in free text from which nuclide and incident neutron-energy the fission-neutron spectrum is resulting.

In the latter case it should be noted that it is essential to give the assumed spectrum type and its parameters, as well as how the fit was made (e.g. in a N(E)-versus-E scale or in a $N(E)/\sqrt{E}$-versus-E scale.

Fission spectrum average cross-sections are defined as

$$\bar{\sigma} = \frac{\int \sigma(E)\ N(E)\ \sqrt{E}\ dE}{\int N(E)\ \sqrt{E}\ dE}$$

Concluding Remarks

The knowledge of the shape of the fission-spectrum is developing, and Maxwellian and Watt spectrum are now considered only as rough approximations. Presently preferred is a "double Watt spectrum", and the Cf-252 spectrum which is more accurately known suggests that none of the presently used fits is sufficient. Therefore, it is most important to compile point-data of the energy-distribution of fission-neutrons. However, mean-energy values are also desirable to compile because they are rather independent of the spectrum shape assumed and frequently needed for measurement analysis (detector response, etc.). (Lemmel)

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FIS-YLD 1)

Fission-Yields

Review-article see e.g. A.C. Pappas, J. Alstad, 69VIENNA,,669,6907.

Fission-process: The capture of the incident neutron creates a highly excited compound-nucleus showing large deformation which leads to scission or to other competing reactions like neutron-evaporation or gamma-emission. At the scission-stage the nucleus generally devides into two deformed and excited fission fragments. In a small fraction of the scissions the nucleus devides into three fragments, where the size of the third fragment varies between a scission-neutron and a fragment similar in size to the other two. (See Ternary Fission). These fragments are called primary, initial, or pre-neutron emission fragments.

The primary fragments repel each other, obtain their full kinetic energy (e.g. 90 MeV), emit prompt neutrons ($< 4 \times 10^{-14}$ sec) and gamma-rays ($< 10^{-11}$ sec), are slowed down in the surrounding medium and stopped. These fragments are called secondary, final, post-neutron emission fragments, or primary fission-products. (The emitted gamma-rays may cause conversion betas and X-rays.)

The primary products undergo (after 10^{-2} sec and more) a series of beta-decays forming secondary products and end up in stable nuclei. For certain products the emission of delayed neutrons is competing with the beta-decay process.

In most of these stages mass-yields and charge-dispersions are measured as well as energy-distributions. The terms "fragments" and "products" are not clearly distinguished. Most frequently "fission-fragments" are meant as primary fragments and "fission-products" are the end-products. However, the border-line between fragments and products is varying, and often the word "fragments" is used as overall term including all stages of decay. Often fission-fragments are specified by their mass only including all Z-numbers. so that the fragment-yield remains constant during beta-decay. Fission products are usually specified by Z and A. A specified fission-product is obtained in two ways: either immediately from fission (primary yield) or from the decay of another fission product. Thus, the total amount of a specified fission-product varies in time. Very short-living fission-products may nevertheless be most important. because some have extremely high capture cross-sections (10^6 b). Finally, all decay to stable end-products, partially via metastable states. For odd A-numbers there exists only one stable end-product, that is significantly formed in fission, for even A-numbers one or two.

Units:
A mass-yield or fission-product yield, when measured absolutely, is given in per-cent per fission (code: PC/FIS). See Example 14. Fissions and fragments must then be counted independently. If only relative yields are given, the modifier REL should be used with the Isoquant and the DATA-Unit code is ARB-UNITS. Since in ternary fission more than two fragments are formed per fission, the yields for all fragments sum up to a bit more than 200%. However, emission of light particles in ternary fission does not change the sum of yields in the binary fission mass range usually measured, and other mass splits in ternary fission are negligible. Therefore relative yield measurements (ARB-UNITS) may be normalized to 200%, if the measurement was made for a sufficient large number of fragments; if this is done, the data-table may include some values that have not been measured but obtained by interpolation; such values must be labelled by flags. Different ways to obtain absolute yields will be discussed in a forthcoming LEXFOR entry about fission yield measurement methods.

Primary fission-fragment-yield. This is the primary yield per fission of fission-fragment mass A before prompt neutron-emission. It may also be called pre-neutron-emission fragment-mass distribution. Quantity-code: NF,YLD,PRE. See Example 14.a. In all experimental techniques corrections for some prompt neutrons already emitted cannot be avoided.

Secondary fission-fragment yield. This is the secondary yield per fission of fission-fragment mass A after prompt-neutron emission, but before beta-decay and delayed neutron-emission. It may also be called post-neutron-emission fragment-mass distribution. Quantity-code: NF,YLD,SEC. See Example 14.a.

Independent fission-product yield. This is the direct or independent yield per fission of a primary fission-product specified by Z and A, after prompt neutron emission, but before beta-decay and delayed-neutron emission, including only the direct yield and not the yield obtained from decay of other fission-products. See Example 14.b. Quantity-code: NF.YLD,IND.

Sum-rule: $\sum_{\substack{\text{all } Z \\ A=\text{const}}}$ NF,YLD,IND = NF,YLD,SEC

Note: Experimental data of independent yields of the product Z.A include a portion yielding from the delayed neutron-emission of the product Z.A + 1 or from the beta-decay of the product Z-1.A, if separation times are not short against the relevant decay-times. Corrections are required which should be mentioned under "CORRECTION". Fragment-mass yields are not affected by beta-decay but only by delayed neutron-emission.

Cumulative fission-product yield. This is the cumulative yield per fission of a fission-product specified by Z and A, after prompt neutron-emission, including the independent yield plus the yield from decay of other fission-products. See Example 14.b. Quantity-code: NF,YLD,CUM.

Sum-rule:

NF,YLD,CUM for the β-decaying product Z-1.A
+ NF,YLD,IND for product Z.A

= NF,YLD,CUM for product Z.A, if the products Z-1.A and Z.A + 1 are not delayed neutron-emitters.

The following events may add to the cumulative yield of the fission-product Z.A in its ground-state:

- independent yield from fission
- beta-decay from product Z-1.A in ground-state
- beta-decay from product Z-1.A in a metastable state
- delayed neutron-emission from product Z.A + 1
- internal transition from a metastable state of product Z.A

In addition, the product Z.A may be formed from neutron capture in the product Z.A-1, which is not included in the "cumulative yield".

The cumulative yield is often given for a metastable state of a fission-product Z.A; this is entered in EXFOR by means of flags, see Example 16.

Total chain-yield. The total chain-yield per fission of fission-fragment mass A is the sum of the cumulative yields of all stable fission-products having the same mass A. See Example 14.a. In the case that only one stable fission-product per mass A exists, the total chain-yield for mass A is identical with the cumulative yield of the stable end-product Z.A.

Fractional yields.
The fractional independent fission-product yield is defined relative to the cumulative fission-product yield or relative to the total chain-yield.

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FIS-YLD 3)

The fractional cumulative fission-product yield is defined relative to the total chain-yield.

In all cases the data are entered as ratios of iso-quants. See Example 14.c.

((92-U-235,NF,YLD,IND)/(92-U-235,NF,YLD,CUM))
((92-U-235,NF,YLD,IND)/(92-U-235,NF,YLD,CHN))
((92-U-235,NF,YLD,CUM)/(92-U-235,NF,YLD,CHN))

The distribution of charge Z within a given fragment mass-chain A is called charge-dispersion. See Example 15.a. It can empirically be approximated by a Gaussian distribution with a most probable charge Zp. See Example 15.b. The fractional independent yield of a fission product (after prompt neutron emission) is given by

$$P(Z) = (\pi c)^{-1/2} \exp[-(Z-Z_p)^2/c] ,$$

whereas the fractional cumulative yield is given by

$$\sum_{0}^{Z} (P_n) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{Z+1/2} \exp\left\{ \frac{-(n-Z_p)^2}{2\sigma^2} \right\} dn$$

The parameters c and σ are widths of the distributions, related by $c \approx 2(\sigma^2 + 1/12)$
For charge dispersion, fractional yields are defined only as ratios to total chain yield.

Reference:

A.C. Wahl et al. Phys. Rev. 126, 1112 (5/62)

Note: The Gaussian width parameter has been assumed to be approximately constant for all A chains, as given by Wahl et al. Therefore Zp has sometimes been determined from a single fractional yield measurement. However, there is evidence for a variation of c and σ with mass A and they may be determined together with Zp. Therefore in a comment the Gaussian width parameter used should be explained (value or reference).

The following definition of charge distribution (primary charge function) is now generally accepted: distribution of primary charge as a function of primary mass. This quantity is deduced, either from other quantities (charge dispersion, mass distribution), or from instrumental measurements of fragment mass (kinetic energy) and X-rays, both methods involving uncertain corrections for prompt neutron emission. As this quantity is mainly of interest for studies of the fission process, but not in applied fields, no codes are proposed. (Lammer)

Note: Angular distributions and energy-spectra of fission fragments are coded as NF,DA,,FF and NF,DE,,FF and similar codes given in dictionary 14.

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SPA

Spectrum Average

Cross-sections averaged over an incident neutron-spectrum are coded with the quantity-modifiers MXW, FIS or SPA in the third quantity-subfield. The type of the spectrum must be specified under the keyword "INC-SPECT".

The code MXW is used for Maxwellian thermal spectra. The temperature of the spectrum must be given in free text under the keyword "INC-SPECT".

The code FIS is used for fission-neutron spectra. For details see the Lexfor-entry on Fission-Neutron Spectra Data, section 3.).

The code SPA is used for all other spectra, reactor pile spectra, etc.

A cross-section given for a thermal spectrum must be coded with

* SPA if the spectrum has a non-negligible epithermal part
* MXW if the result has been corrected for the epithermal part of the spectrum, or if the epithermal part is negligible.

In the Westcott formalism (see AECL-1101) a cross-section averaged over a thermal reactor spectrum is described as:

$\hat{\sigma} = \sigma_0 (g + rs)$ coded as, e.g., ABS,,SPA

where σ_0 = cross-section at $E_n = 0.0253$ eV (2200 m/s), coded as, e.g., ABS

g,s are factors depending on the shape of the $\sigma(E)$ curve considered

r is a measure of the proportion of epithermal neutrons in the spectrum with r = 0 for a Maxwellian spectrum

$g\sigma_0$ = Maxwellian averaged cross-section coded as, e.g., ABS,,MXW.

To facilitate that spectrum averaged data are included in a data retrieval by energy, an artificial energy-value is entered under the data-heading keyword "EN-DUMMY". The numerical values to be given under this heading are

0.0253 eV for Maxwellian and pile thermal spectra
1.5MeV for fission-spectra
(no dummy-energy is entered for spontaneous fission).
For other spectra, an appropriate value is to be entered under EN-DUMMY.

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Ex

EXAMPLES OF EXFOR-CODING

1. sample of an EXFOR transmission tape
2. data-headings RATIO, STAND, DATA
3. "ℓ" as parameter for reduced neutron-width
4. normalization
5. data-units, relative data, degrees and minutes
6. authors, status, history
7. error-columns
8. flags
9. differential partial inelastic data
10. double-differential inelastic data
11. relative differential data
12. unresolved levels
13. two-dimensional tables, TABLE-NR
14. fission-yields
15. fission-product charge: charge dispersion
16. relative cumulative yields of metastable fission-products

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Ex 14

Example 14: Fission-yields

a) Primary fission-fragment yield:

```
ISO-QUANT    (92-U-235,NF,YLD,PRE)
...
COMMON
EN
EV
0.0253
ENDCOMMON
DATA
MASS         DATA
NO-DIM       PC/FIS
...          ...
```

The secondary fission-fragment yield is entered as above; only the quantity-modifier PRE is replaced by SEC. The total chain-yield has the modifier CHN instead.

b) Independent fission-product yield:

```
ISO-QUANT    (92-U-235,NF,YLD,IND)
...
COMMON
EN
EV
0.0253
ENDCOMMON
DATA
ELEMENT     MASS        DATA
NO-DIM      NO-DIM      PC/FIS
...         ...         ...
```

The cumulative fission-product yield is entered as above; only the quantity-modifier IND is replaced by CUM.

c) Fractional yields:

```
ISO-QUANT    ((92-U-235,NF,YLD,IND)/(92-U-235,NF,YLD,CHN))
...
COMMON
EN
EV
0.0253
ENDCOMMON
DATA
ELEMENT     MASS        RATIO
NO-DIM      NO-DIM      NO-DIM
...         ...         ...
```

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Ex 15

Example 15: Fission-product charge: charge dispersion

a) Fractional yields

```
ISO-QUANT    ((92-U-235,NF,YLD,IND)/(92-U-235,NF,YLD,CHN))
...
COMMON
MASS         EN
NO-DIM       EV
135.         0.0253
ENDCOMMON
DATA
ELEMENT      RATIO
NO-DIM       NO-DIM
53.          ...
54.          ...
55.          ...
...          ...
```

Fractional cumulative yields are entered as above, with IND replaced by CUM. For charge dispersion the second isoquant of the ratio must always have the modifier CHN.

b) Most probable charge

```
ISO-QUANT    (92-U-235,NF,ZP)
...
COMMON
EN
EV
0.0253
ENDCOMMON
DATA
MASS         DATA
NO-DIM       NO-DIM
```

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Ex 16

Example 16: Relative Cumulative yields of metastable fission-products

```
BIB
...
ISO-QUANT   (92-U-235,NF,YLD,CUM/REL)
FLAG        (0.) FISSION-PRODUCT IN GROUND-STATE
            (1.) FISSION-PRODUCT IN FIRST METASTABLE STATE
...         NOT FLAGGED = FIS.PROD. WITHOUT METASTABLE STATE
ENDBIB
COMMON
EN
EV
0.0253
ENDCOMMON
DATA
ELEMENT    MASS      FLAG      HL       DATA
NO-DIM     NO-DIM    NO-DIM    D        ARB-UNITS
50.        118.                         ...
50.        119.      0.                 ...
50.        119.      1.        ...      ...
50.        120.                         ...
50.        121.      0.        ...      ...
50.        121.      1.        ...      ...
50.        122.                         ...
50.        123.      0.        ...      ...
50.        123.      1.        ...      ...
51.        123.                         ...
...        ...       ...       ...      ...
ENDDATA
```