Beta-delayed Neutron Emission Probability and Multiplicity

(O. Schwerer et al., Memo CP-C/429, V. Semkova, et al., Memo 4C-3/396)

Memo CP-C/429 (2014-05-23)

After discussions during and after the NRDC meeting, we propose some modifications and additions to the coding proposed in 4C-3/396 and CP-D/837, as follows:

The delayed neutron emission probability (=probability for emission of at least one beta-delayed neutron), P_n, is coded as `,PN` with units `NO-DIM`.
The probability of emission of N beta-delayed neutrons, P_{Nn}, is coded as `NUM,PN` with units `NO-DIM`. *(No change from 4C-3/396)*
The delayed-neutron emission multiplicity, <n>, is coded as `,MLT,DN` with units `PRT/DECAY` or `PC/DECAY`.
The energy spectrum of delayed neutrons emitted by a specific precursor is coded as `,PN/DE` with units of dimension `1/E`. *(Modified from CP-D/837)*

Appended below are the proposed revised Lexfor page D.6 and a summary of the necessary dictionary updates.

Revised LEXFOR page D.6 (last part of chapter „Delayed Fission Neutrons“)

Delayed-Neutron Emission Probability (P_n value)

Definition: Probability for emission of at least one β-delayed neutron

REACTION Coding: `(Z-S-A(0,B-)[Z+1]-S'-A,,PN)`

Units: `NO-DIM`

For delayed neutron emission probabilities see for example, Amarel [4], Tomlinson [5], and Asghar [6].

Probability of emission of N β-delayed neutrons (P_{Nn})

Definition: Probability to emit N neutrons after β decay

REACTION Coding: `(Z-S-A(0,B-)[Z+1]-S'-A,NUM,PN)`

Units: `NO-DIM`

The number of emitted neutrons is given under the data heading `PART-OUT` with units `NO-DIM`.

Delayed-neutron emission multiplicity <n>

Definition: Multiplicity of delayed neutrons per decay

$<n> = P_{1n} + 2*P_{2n} + 3*P_{3n} + \ldots$

REACTION Coding: `(Z-S-A(0,B-)[Z+1]-S'-A,MLT,DN)`

Units: `PRT/DECAY` or `PC/DECAY`

Energy spectrum of delayed neutrons emitted by a specific precursor

REACTION Coding: `(Z-S-A(0,B-)[Z+1]-S'-A,,PN/DE)`

Units: a code from Dictionary 25 with dimension `1/E` (*e.g.*, `1/KEV`)

1.

1. From the above definitions follows $P_n = P_{1n} + P_{2n} + P_{3n} + \ldots$
If only one neutron emission is energetically possible, $P_n = P_{1n} = <n>$, the coding `,PN` must be used.

1. **Data not Presently Compiled in EXFOR**

- The energy spectrum of all delayed neutrons together, which is time dependent, due to the contributions from the different half-life groups.
- The delayed-neutron equilibrium spectrum as found in a steady-state reactor.

References

[1.] S. Amiel, *IAEA Panel on Fission-product Nuclear Data*, Bologna, 1973, IAEA report IAEA-169, Vol. II (1973) p. 33

[2.] G.R. Keepin, Physics of Nuclear Kinetics (Addison-Wesley, 1965) Chapter 4

[3.] E.K. Hyde, The Nuclear Properties of Heavy Elements, Vol. III (Prentice Hall, 1964) p. 261 ff.

[4.] I. Amarel, *et al*., J. Inorg. Nuc. Chem., **31**, 577 (1969)

[5.] L. Tomlinson, *et al*., J. Inorg. Nuc. Chem., **33**, 3609 (1971)

[6.] M. Asghar, *et al*., Nucl. Phys. **A247**, 359 (1975)

[7.] I. Dillmann, *et al*., (ed.), INDC(NDS)-0643, IAEA, Vienna (2014)

(End of Lexfor page)

Related dictionary updates

Dictionary 25 (Data Units)

Change:

PC/DECAY	*change definition to:* Particles per 100 decays

Add:

PRT/DECAY	Particles per decay

Dictionary 33 (Particles)

Change:

DN *Add flag 7*

Dictionary 213 (Reaction Type)

Add:

PNE	NUD	MFQ	4* 3	Delayed neutron spectrum from individual precursor

Dictionary 236 (Quantities)

Change:

,PN *Change unit dimension to* NO

Add:

,MLT,DN	MLT	PN	Delayed neutron emission multiplicity
NUM,PN	PN NO		Probability of emission of N delayed neutrons
,PN/DE	PNE	1/E	Spectrum of delayed neutrons emitted by specific precursor

4C-3/396 (2014-04-30)

If the β^- decay energy (Q_β) is larger than the two or more neutron separation energy ($S_{2n,\ 3n...}$) of the product of the decay a process of multiple neutron emission may take place. The following quantities are defined for the cases when $Q_\beta - S_{xn} > 0$ (x=1,2,...):

- P_{xn} (x=1,2,3): probability to emit x β-delayed neutrons per decay
- P_n: probability to emit at least one β-delayed neutron per decay ($P_n = P_{1n}+P_{2n}+P_{3n}+...$)
- P'_n: multiplicity of β-delayed neutrons per decay ($P'_n = P_{1n}+2P_{2n}+3P_{3n}+\ldots$)

The current description LEXFOR "Delayed Fission Neutrons" does not distinguish the multiplicity from probability. In the relation with the IAEA CRP on "Development of reference database for beta-delayed neutron emission", we foresee compilation of above three quantities. We propose to keep the current quantity code `,PN` for the multiplicity P'_n, and also to add new quantity codes for P_{xn} and P_n.

Dictionary 236 (Quantities)

`NUM,PN`: probability for emission of N beta-delayed neutrons

`UNW,PN`: probability for emission of at least one beta-delayed neutrons

`,PN`: multiplicity of beta-delayed neutrons ($P'_n = P_{1n}+2P_{2n}+\ldots$)

Quantity	Reaction Type	Dimension
NUM,PN	PN	NO
UNW,PN	PN	NO
,PN	PN	PN

There is no consistent nomenclature established in the literature and P_n value is referred in some articles to the β-delayed neutron emission probability and in other articles to the multiplicity. However, the compilers should verify the meaning of the determined quantity. Free text explanation could be useful for users as well. For cases when only 1 beta-delayed

neutron emission is feasible $P'_n \equiv P_n$. For consistency of the compilation in such cases ~~UNW~~,PN coding is proposed.

In order to make each data set searchable not only by the precursor nuclide but also by the decay product, we would like to forbid use of the variable nuclide formalism ELEM/MASS in REACTION SF1 and to code the decay product always in REACTION SF4.

Revision to the LEXFOR entry is proposed at the end of this memo.

Example

Table 1 of T.Björnstad et al., Delayed neutron emission probabilities of ^{11}Li**,** Nucl. Phys. A359 (1981) 1

Quantity	Probability (%)
P_{1n}	85±1
P_{2n}	4.1±0.4
P_{3n}	1.9±0.2
P_n	91±1
P'_n	98±1

(P_n value is not given in this article, but calculated for explanation of the coding rule.)

```
SUBENT        01230002   20140417
BIB
REACTION   (3-LI-11(0,B-),NUM,PN)
STATUS     (TABLE) Text (p6) of Nucl.Phys.A359(1981)1
ENDBIB
NOCOMMON
DATA
PART-OUT   DATA       DATA-ERR
NO-DIM     NO-DIM     NO-DIM
 1.        0.85       0.01
 2.        0.041      0.004
 3.        0.019      0.002
ENDDATA
ENDSUBENT
SUBENT        01230003   20140417
BIB
REACTION   (3-LI-11(0,B-),UNW,PN)
STATUS     (TABLE) Private communication
ENDBIB
NOCOMMON
DATA
DATA       DATA-ERR
NO-DIM     NO-DIM
 0.91       0.01
ENDDATA
ENDSUBENT
SUBENT        01230004   20140417
BIB
REACTION   (3-LI-11(0,B-),,PN)
COMMENT    Average multiplicity of beta-delayed neutron
```

```
STATUS    (TABLE) Text (p6) of Nucl.Phys.A359(1981)1
ENDBIB
NOCOMMON
DATA
DATA      DATA-ERR
PC/DECAY  PC/DECAY
 98.        1.
ENDDATA
ENDSUBENT
```

LEXFOR Entry (Addition and deletion to "Delayed fission neutrons")

Delayed-Neutron Emission Multiplicity (<n>)

Definition: Multiplicity of β-delayed neutron per decay

REACTION Coding: `(Z-S-A(0,B-)Z'-S'-A',,PN)`

where `Z-S-A` is the precursor nucleus (i.e., before β-decay)
`Z'-S'-A'` is the decay product nucleus (i.e., after β-decay)

Units: a code from Dictionary 25 with dimension `PN` (*e.g.*, `PC/DECAY`)

Delayed-Neutron Emission Probability (P_n value)

~~**Definition**: Neutron yield per β decay for a given nucleus. This is a decay quantity of the fission product nucleus and is independent of the fissioning target nucleus. It is related to the fission yield by~~

~~P_n = absolute delayed neutron yield / cumulative fission yield~~

~~**REACTION Coding**:~~

~~a. `((Z-S-A(0,B-)Z'-S'-A',,PN)` for a single fragment~~
~~where: *Z-S-A* is the fission product nucleus (precursor nucleus before β decay);~~
~~*Z'-S'-A'* is the delayed-neutron emitting fission fragment.~~

~~b. `(ELEM/MASS(0,B-),,PN)` for a series of fragments~~
~~The fission product nucleus is entered as a variable in the data table (see EXFOR Chapter 6: Variable Nucleus).~~

~~**Units**: a code from Dictionary 25 with dimension `PN` (*e.g.*, `PC/DECAY`)~~

Definition: Probability for emission of at least one β-delayed neutron

REACTION Coding: `(Z-S-A(0,B-)Z'-S'-A',UNW,PN)`

Units: a code from Dictionary 25 with dimension `NO` (*e.g.*, `NO-DIM`)

Delayed-Neutron Emission Probability (P_{Nn} value)

Definition: Probability to emit N β-delayed neutrons (P_{1n}, P_{2n},…)

REACTION Coding: `(Z-S-A(0,B-)Z'-S'-A',NUM,PN)`

Units: a code from Dictionary 25 with dimension `NO` (*e.g.*, `NO-DIM`)

The number of emitted neutrons is give under the data heading `PART-OUT` with units of `NO-DIM`.

From these definitions $P_n=P_{1n}+P_{2n}+\ldots$ and $<n>=P_{1n}+2P_{2n}+\ldots$ Especially $P_n=<n>$ only one neutron emission is energetically possible, and ,PN must be always used. Note that some authors use the symbol "P_n" not for the probability but for the multiplicity.

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