Memo issued on behalf of
National Nuclear Data Center
Brookhaven National Laboratory
USA

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To: Distribution
From: O. Schwerer

Subject: **Final and intermediate reaction products**

In EXFOR REACTION coding, as a rule, the final products of a nuclear reaction will be coded in REACTION SF4 and/or SF3. Intermediate states, such as excited states unstable against prompt particle emission, will not normally appear as reaction products. Such levels may be defined using EN-SEC and E-LVL or E-EXC, in particular, when competing channels have to be distinguished.

This rule is, in general, sufficiently clear for neutron reactions and has been largely observed. However, for charged-particle and heavy-ion-induced reactions, more complicated reactions occur and clarification is required, in particular in view of recent discussions.

1. Neutron reactions

An important case concerns "inelastic" excitation of states unstable against particle emission, followed by prompt decay into the final products.

A classical case is the reaction which in the literature is usually written as

^{12}C(n,n')3α

This reaction must be coded as `6-C-12(N,N+2A)2-HE-4`
(see LEXFOR, **"Light-Nuclei Neutron Reactions",** page L.3).
Note that this is the only correct coding for this reaction. SF3=INL is not a valid option for this channel.

This LEXFOR page lists several other reactions which are likely to occur in the literature as "inelastic" or (n,n') reactions followed by prompt particle decay. None of them should be compiled with INL in SF3 but all with the final products in SF3 and SF4. Examples are ^{11}B(n,nα)^{7}Li, ^{10}B(n,n^{3}He)^{7}Li, ^{9}Be(n,nd)^{7}Li, etc.

The LEXFOR page **"Light-Nuclei Reactions"** (page L.1) also says that competing reactions leading to the same end products may exist (implying that still those end products will be given in the REACTION while the different channels will be defined using EN-SEC and E-LVL).

2. Charged-particle and heavy-ion induced reactions

With charged particles and heavy ions as projectiles, the situation of excitation of states unstable against prompt particle emission extends also to the projectile. In particular in view of experiments

in inverse kinematics or, generally, with the projectile sometimes heavier than the target, there is no reason why excited and decaying projectiles should be treated differently from excited targets.

We therefore propose to clarify the situation by making this rule (to always code the final reaction products in SF4, or SF3 and SF4), which exists implicitly in LEXFOR for neutron reactions, explicitly a general one.

Suggested addition to LEXFOR, "Reaction Product":

Intermediate and final reaction products

In general, the final reaction products are to be coded in REACTION SF4 (or, if several products are produced, in SF4 and SF3). Intermediate states unstable against prompt particle decay will not normally appear as products but may be specified using the keyword EN-SEC and data headings E-LVL or E-EXC.
*Typical cases where such intermediate states are produced are inelastic reactions leading to promptly decaying excited states. See LEXFOR "**Light-Nuclei Neutron Reactions**" for examples of excited target nuclei and how these reactions must be coded. Note that the same rule applies also to excited heavy projectiles unstable against prompt particle emission.*

3. Recent example: ^{9}Be(^{10}C,2p+2α)^{9}Be and ^{12}C(^{10}C,2p+2α)^{12}C

On these reactions, a group including authors R.J. Charity, K. Mercurio et al. recently published 3 papers:

(1) PR/C,80,024306,2009 EXFOR C1732 (on PRELIM/TRANS C095)
(2) PR/C,78,031602,2008 EXFOR C1660
(3) PR/C,75,51304,2007 EXFOR C1580

(1) The preliminary version of entry C1732 (PRELIM C095) was compiled with SF1-SF4 as explained above. In the final version, additional information about intermediate states was added using EN-SEC and E-LVL1,2. In addition, in some cases free text explanations about the reaction channels is added as "footnotes" using FLAG. This is not strictly necessary because the data are distinguishable by the information given in COMMON and DATA sections, but is considered useful for the users.

(2) Entry C1660 (on master): REACTION coding
(6-C-12(6-C-10,2P+2A)6-C-12....)
is in agreement with the present proposal.

(3) Entry C1580 (on master): REACTION coding
(4-BE-9(6-C-10,INL)4-BE-9....)
is inconsistent with both, the coding of entry C1732 (describing a repetition of the same experiment) and the present proposal. This entry will be retransmitted replacing REACTION SF3=INL with the final products.

4. Concerns about retrievability

The main motivation for the standardization of REACTION coding for light-particle reactions (where a priori often several possibilities exist), as described in LEXFOR "Light-Nuclei Reactions", was the unambiguous retrievability. Nevertheless, a novice user may need more than one trial to find the ^{12}C(n,n')3α data under the (n,n+2a) reaction. Anyway our rule makes sure that these data are compiled under only one REACTION code.

On the other hand, this problem is actually less severe in cases of "decaying projectiles" as described above under 3. Even if we think of such data as "inelastic", REACTION SF1, SF2, and SF4 remain the same, and therefore the data can conveniently be retrieved with these 3 parameters, ignoring the contents of SF3 (which may be thought of being "INL" but is actually something like 2P+2A).

5. General considerations

When clarifying our rules for more precise REACTION coding, I believe the following considerations are important:

- Detailed coding for certain types or branches of REACTIONs is defined not only through REACTION SF1-SF4 but also using SF5-SF8 (e.g. with branch codes SEQ or PAR) and sometimes specified further using EN-SEC and the related numerical values for secondary energies.

- SF3=INL is used (only) for inelastic scattering as the process which was measured but not in combination with other outgoing particles. The only combination of INL with another code within SF3 occurring in the master file is (...,INL+F) e.g. for (n,n'f). I believe that this restriction is correct and need not be changed. (One could even discuss changing (N,INL+F) to (N,N+F).)

- When proposing changes in REACTION coding rules, the following practical considerations should be taken into account:

    - Reasonable simplicity for compilers (i.e., they can determine the correct REACTION coding easily enough from the publication, normally without much checking back with the authors)

    - Reasonable simplicity for the users (i.e., for data which are usually retrieved together and have SF1-SF4 in common, it may be a good option to be compiled under the same REACTION and be distinguished only by "secondary" elements such as different values of E-LVL or different nuclides under EN-SEC). In other words, we should check how useful it is to split certain reactions into (too) many branches

    - How will the new rule affect existing entries - how many will have to be retransmitted for consistency, and how easy will it be to do this accurately

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