Nuclear Data Section
International Atomic Energy Agency
P.O.Box 100, A-1400 Vienna, Austria

<u>Memo CP-D/631</u>

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To: Distribution
From: N. Otsuka, S. Takács

Subject: Production thick target yield

The production (unsaturated, time-dependent) yield is proportional to the beam current, but not proportional to the irradiation time. (e,g, irradiation for 1 hour with 2 μA does not give the same activity as 2 hours and 1 μA irradiation.. See also Eqs.(3) and (4) in the appendix.) The production yield is a function of the irradiation time and its unit should be Bq/μA rather than Bq/μA•hr. IAEA-TECDOC-1211 (Charged-Particle Cross Section Database for Medical Radioisotope Production. Diagnostic Radioisotopes and Monitor Reactions) also does not put "hr" for the units of production thick target yield. Therefore we propose to change the dimension of this quantity (SF8=DT) from TTT to TTY. The affected is summarized in the table in next page.

We also propose the following rule:

1) Because the production yield depends on irradiation time, the irradiation time should be coded in free text for production yield.

2) Compilers should not decide the quantity code and its unit codes based on the authors' notation because there is no consistency in their expression. It should be decided by the definition of the data given (with consultation of authors when the definition is not clear in the article). If authors give production yield, it should be coded by Bq/μA even if the authors use Bq/μA•hr.

3) Physical thick target yield is usually derived from integration of the excitation function of cross section. Therefore we should not use DERIV in SF9 when authors derived physical thick target yield from the experimental cross section measured in the work.

Physical thick target yields are coded as production thick target yield:
D4083.005, D4109.003, 005, 007, 009, D4110.004, D4111.006-012
, where modifier DT should be replaced by PHY.

Thick target yields defined in EXFOR is summarized in Appendix.

Proposed correction of dimension (Unit family)

Unit (Dict.25)

Code	Expansion	Dim.	Should be
DPS/MUAHR	decays per Sec/micro-Ampere-hour	TTT	
GBQ/COUL	Giga-Becquerel/Coulomb	TTT	
KBQ/MUAHR	kilo-Becquerel/micro-Ampere-hour	TTT	
MBQ/COUL	Mega-Becquerel/Coulomb	TTT	
MBQ/MUAHR	Mega-Becquerel/micro-Ampere-hour	TTT	
MCI/MUAHR	milli-Curie/micro-Ampere-hour	TTT	
MUCI/MUAHR	micro-Curie/micro-Ampere-Hour	TTT	
CI/AHR/MEV	Curie per Ampere-hour per MeV	TTTE	
MBQ/C/MEV	Mega-Becquerel/Coulomb/MeV	TTTE	
GBQ/MUA	Giga-Becquerel/micro-Ampere	TTY	
MBQ/MUA	Mega-Becquerel/micro-Ampere	TTY	
MCI/MUA	milli-Curie/micro-Ampere	TTY	
MUCI/MUA	micro-Curie/micro-Ampere	TTY	
PART/MUAHR	particles/micro-Ampere-hour	TTY	TTT

Quantities (Dict.236)

Code	Expansion	Dim.	Should be
,TTY/DA,,DT	(Diff.prod.thick/thin target yield)	TTDA	Unused. Delete.
(CUM),TTY,,DT	(Production thick/thin target yld(assum.cum.	TTT	TTY
(M),TTY,,DT	(Production thick/thin-target yld,(uncert.	TTT	TTY
,TTY,,DT	(Production thick/thin-target yield)	TTT	TTY
,TTY,,PHY	(Physical thick/thin-target yield)	TTT	
CUM,TTY,,DT	(Cum.production thick-target yield (unsat.))	TTT	TTY
CUM,TTY,,PHY	(Physical thick/thin-target yield,	TTT	
CUM/UND,TTY,,DT	(Cumul.thick-target yield/unit time,undef.	TTT	TTY
IND,TTY,,DT	(Indep.production thick/thin-target yld	TTT	TTY
IND/M+,TTY,,DT	(Ind.production thick-target yld incl.isom.	TTT	TTY
IND/UND,TTY,,DT	(Indep.thick-target yield/unit time,undef.	TTT	TTY
M+,TTY,,DT	(Thick-target yield per unit time incl.isom.	TTT	TTY
M+,TTY,,PHY	(Physical thick/thin-target yield incl.isom.	TTT	
M+/UND,TTY,,DT	(Thick-targ.yld/unit time incl.isom.tr.,	TTT	TTY
M-,TTY,,DT	(Product.thick/thin target yield excl.isom.	TTT	TTY
UND,TTY,,DT	(Thick-target yield per unit time, undef.	TTT	TTY
,TTY,,TM	(Prod.thick target yield/1 MeV thn.)	TTTE	
,TTY/DE,,DT	(Diff.production thick target yield d/dE)	TTTE	Unused. Delete.
(CUM),TTY	(Sat.thick/thin target yield(assumed cumul.	TTY	
(M),TTY	(Thick-target yield (uncert.if isom.trans.)	TTY	
,TTY	(Saturated thick/thin-target yield)	TTY	
,TTY/DA	(Diff.satur.thick target yield d/dA)	TTY	
CUM,TTY	(Saturated cumul.thick/thin target yield)	TTY	
CUM/(M),TTY	(Cum.thick-target yield (uncert.isom.trans.	TTY	
CUM/M-,TTY	(Cum.satur.thick-target yield,exclud.isom.	TTY	
CUM/UND,TTY	(Cumulative thick-target yield, undefined	TTY	
IND,TTY	(Independent thick-target yield)	TTY	
IND/M+,TTY	(Ind.satur.thick/thin-target yld,incl.isom.	TTY	
IND/UND,TTY	(Independent thick-target yield,undefined	TTY	
M+,TTY	(Thick-target yield, incl. via isomeric	TTY	

M+/UND,TTY	(Thick target yield,incl.isom.trans.,undef.	TTY
M-,TTY	(Thick-target yield, excluding isomeric	TTY
PAR,TTY	(Partial thick target yield)	TTY
PAR,TTY,G	(Partial thick target gamma yield)	TTY
PAR,TTY/DA	(Partial differential thick target yield	TTY
SEQ,TTY	(Thick target yield for specified reaction	TTY
UND,TTY	(Thick target yield, undefined reaction)	TTY

Appendix: Thick target yields

Definitions:

1. **Thick target product yield**

The number of produced nuclei by one incident particle (charge *Z*) is

$$\int_0^{E_0} \mathrm{d}E\, \sigma(E) \rho \left(\frac{\mathrm{d}E}{\mathrm{d}x} \right)^{-1} \quad \text{[nuclei/incident particle]}$$

This is thick target product yield. The number of produced nuclei after irradiation by current $I(t)$ for t is

$$\left[\frac{1}{Ze} \int_0^{t} \mathrm{d}t'\, I(t') \right] \cdot \int_0^{E_0} \mathrm{d}E\, \sigma(E) \rho \left(\frac{\mathrm{d}E}{\mathrm{d}x} \right)^{-1}$$

If the current $I(t)$ is constant unit current ($I(t) = 1$), we obtain number of produced nuclei after irradiation by unit current for time t

$$N_0(E_0, t) = \frac{t}{Ze} \int_0^{E_0} \mathrm{d}E\, \sigma(E) \rho \left(\frac{\mathrm{d}E}{\mathrm{d}x} \right)^{-1} .$$

Then the number of produced nuclei by unit current per unit time is

$$n_0(E_0) \equiv \frac{\mathrm{d}N_0(E_0, t)}{\mathrm{d}t} = \frac{1}{Ze} \cdot \int_0^{E_0} \mathrm{d}E\, \sigma(E) \rho \left(\frac{\mathrm{d}E}{\mathrm{d}x} \right)^{-1} \qquad (1)$$

This is also thick target product yield.

2. **Physical thick target yield**

The activity of thick target product yield

$$y(E_0) = \lambda n_0(E_0) \qquad (2)$$

is defined as physical thick target yield (*Y* in IAEA-TECDOC-1211).

3. **<u>Production thick target yield</u>**

Considering decay of the produced nuclei, the number of living nuclei after irradiation by unit current $N(E_0,t)$ satisfies

$$\frac{\mathrm{d}N(E_0,t)}{\mathrm{d}t} = n_0(E_0) - \lambda N(E_0,t)$$

. The solution of this equation is

$$N_t(E_0) \equiv N(E_0,t) = n_0(E_0)\frac{1-e^{-\lambda t}}{\lambda} \qquad (3)$$

and its activity

$$A_t(E_0) = \lambda N_t(E_0). \qquad (4)$$

is defined as <u>production thick target yield</u>. From this definition, production thick target yield depends on irradiation time.

Especially, the number of living nuclei after the unit time irradiation is

$$N_1(E_0) \equiv N(E_0, t=1) = n_0(E_0)\frac{1-e^{-\lambda}}{\lambda} \qquad (5)$$

and its activity is

$$A_1(E_0) = \lambda N_1(E_0) \qquad (6)$$

, which is defined as A_1 in IAEA-TECDOC-1211.

4. **<u>Saturation thick target yield</u>**

After infinite irradiation by unit current, the number of living nuclei is

$$N_\infty(E_0) \equiv N_\infty(E_0, t\to\infty) = \frac{n_0(E_0)}{\lambda} \qquad (7)$$

Its activity

$$A_\infty(E_0) = \lambda N_\infty(E_0) \qquad (8)$$

is defined as <u>saturation thick target yield</u> (A_2 in IAEA-TECDOC-1211).

The relations between quantities defined in (1) - (8) are

$$A_t(E_0) = y(E_0)\frac{1-e^{-\lambda t}}{\lambda} = A_1(E_0)\frac{1-e^{-\lambda t}}{1-e^{-\lambda}} = A_\infty(E_0)\left(1-e^{-\lambda t}\right)$$

$$N_t(E_0) = n_0(E_0)\frac{1-e^{-\lambda t}}{\lambda} = N_1(E_0)\frac{1-e^{-\lambda t}}{1-e^{-\lambda}} = N_\infty(E_0)\left(1-e^{-\lambda t}\right)$$

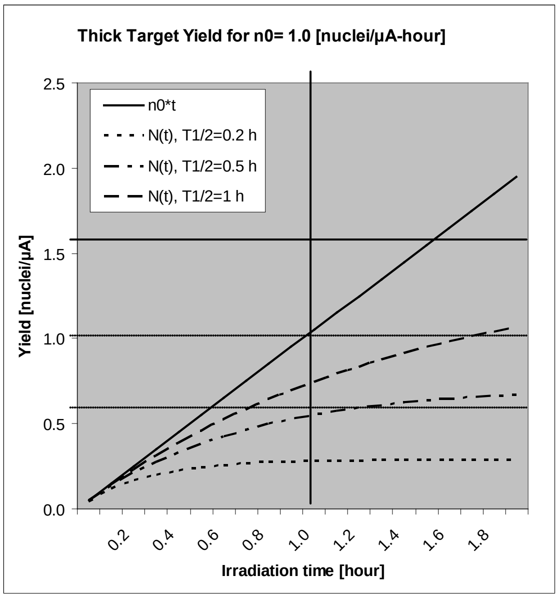

Figure: Time dependence of living number of nuclei for four nuclides which $n_0(E_0)$=1.0 [nuclei/μ A-h]) but half-lives are different ($T_{1/2}$=0.2, 0.5, 1 [h]) . Solid line gives $n_0(E_0)t$ (mumber of produced nuclei) in [nuclei/μ A], and dotted, dash-dotted, dashed lines are $N_t(E_0)$ (number of living nuclei) in [nuclei/μ A]. $N_1(E_0)$ (number of living nuclei after 1 hour irradiation) is 0.28, 0.54, 0.74 [nuclei/μ A] for $T_{1/2}$=0.2, 0.5, 1 [h] cases. $N_\infty(E_0)$ (number of living nuclei after infinite time irradiation) is 0.29, 0.72, 1.40 [nuclei/μ A] for $T_{1/2}$=0.2, 0.5, 1 [h] cases. See Eqs. (2), (4), (5) and (6) for definitions of $n_0(E_0)$, $N_t(E_0)$, $N_1(E_0)$ and $N_\infty(E_0)$.

Units of thick target yield:

- Thick target product yield defined in Eq.(1) is given in [nuclei/incident particle].

If we set the unit current and time as 1 [μ A] and 1 [h], the decay constant is λ [h^{-1}]),.and

Number of *produced* nuclei *per* 1 [h] per 1 [μ A]: $n_0(E_0)$ [nuclei / μ A-h]

Number of *living* nuclei *after* 1 [h] per 1 [μ A]: $N_1(E_0) = n_0(E_0)\dfrac{1-e^{-\lambda}}{\lambda}$ [nuclei/μA]

Number of *living* nuclei after infinite time per 1 [μ A]: $N_\infty(E_0) = \dfrac{n_0(E_0)}{\lambda}$ [nuclei/μA]

Multiplication of λ [h^{-1}]/3600 [s/h] (convert [decays/h] to [decays/s] = [Bq]) leads to

$$y(E_0) = \frac{\lambda}{3600} n_0(E_0) \text{ [Bq/μA-h]}$$

$$A_1(E_0) = \frac{\lambda}{3600} N_1(E_0) = n_0(E_0)\frac{1-e^{-\lambda}}{3600} = \frac{1-e^{-\lambda}}{\lambda} y(E_0) \text{ [Bq/μA]}$$

$$A_\infty(E_0) = \frac{\lambda}{3600} N_\infty(E_0) = \frac{n_0(E_0)}{3600} = \frac{y(E_0)}{\lambda} \text{ [Bq/μA]}$$

Example: ^{124}Te(p,2n)^{123}I $T_{1/2}$=13.23 [h] at 30 MeV (Table 5.1.8b of TECDOC-1211 p191):

y = 289 [GBq/C]=1040 [MBq/μ A-h] (1 [μ A-h]=3600 [C]). λ = ln2/$T_{1/2}$=0.05239 [h^{-1}].This leads to

Production thick target activity after 1 hour irradiation:

A_1=[1-exp(-0.05239)]/0.05239$\times$1040=1013 [MBq/μA]

Saturated thick target activity:

A_{∞}=1040/0.05239=19851[MBq/μA] = 19.9 [GBq/μA]

Distribution:

blokhin@ippe.ru
chiba@earth.sgu.ac.jp
claes.nordborg@oecd.org
emmeric.dupont@oecd.org
ganesan@barc.gov.in
gezg@ciae.ac.cn
hasegawa@nea.fr
henriksson@near.fr
hongwei@ciae.ac.cn
jhchang@kaeri.re.kr
j.roberts@iaea.org
kaltchenko@kinr.kiev.ua
katakura.junichi@jaea.go.jp
kato@nucl.sci.hokudai.ac.jp
kirarlyb@atomki.hu
l.vrapcenjak@iaea.org
manuel.bossant@oecd.org
manokhin@ippe.ru
mmarina@ippe.ru
mwherman@bnl.gov
nicolas.soppera@oecd.org
nklimova@kinr.kiev.ua
n.otsuka@iaea.org
nrdc@jcprg.org
oblozinsky@bnl.gov
ogritzay@kinr.kiev.ua
otto.schwerer@aon.at
r.forrest@iaea.org
samaev@obninsk.ru
s.babykina@polyn.kiae.su
scyang@kaeri.re.kr
s.dunaeva@iaea.org
stakacs@atomki.hu
stanislav.hlavac@savba.sk
taova@expd.vniief.ru
tarkanyi@atomki.hu
varlamov@depni.sinp.msu.ru
vlasov@kinr.kiev.ua
vmclane@optonline.net
v.pronyaev@iaea.org
v.zerkin@iaea.org
yolee@kaeri.re.kr