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Gamma production following quasi-metastable state production

(N. Otsuka, V. Devi, 2023-03-07, Memo CP-D/1057(Rev.))

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Memo CP-D/1057 (Rev.)

Dictionary 33 (particles) defines the following two codes:

`G` Gammas (Use DG for decay gammas)

`DG` Decay gammas – Used for gammas emitted from *metastable states* and for gammas following a particle-emitting decay (e.g., beta decay)

Obviously "metastable state" in the explanation of DG does not include quasi-metastable states (Otherwise all cascade gammas eventually belong to `DG` since we do not have the lower boundary of the half-life for quasi-metastable states.). Then there are probably following three cases for the datasets currently coded with `PAR,$SF6,G`:

1. All cascade gammas (usual gamma production cross section)

   Examples:

   `82-PB-206(N,INL)82-PB-206,PAR,DA,G`

   for the full portion of the 803 keV gamma production

   `13-AL-27(N,INL)13-AL-27,PAR,DA,G`

   for the full portion of the 1014 keV gamma production excluding decay gamma originating from $^{27}Al(n,p)^{27}Mg$ (9.5 min)→^{27}Al.

2. Cascade gammas not following quasi-metastable state ($T_{1/2}$<0.1 sec) production - This could be coded with a new modifier (say `L-`) indicating "excluding formation via quasi-metastable state production".

   Example (proposal):

   `82-PB-206(N,INL)82-PB-206,PAR/L-,DA,G`

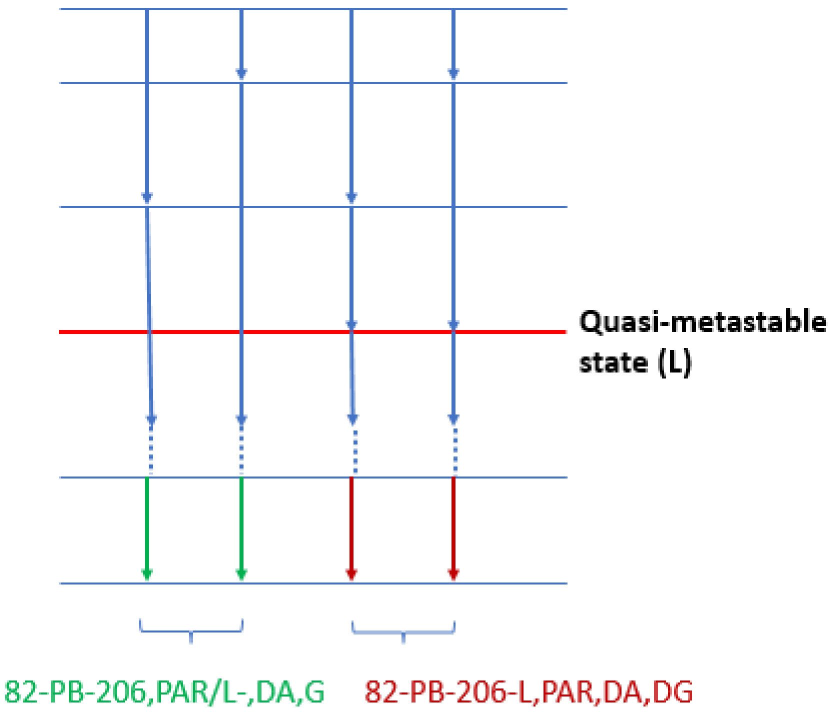
   for the 803 keV gamma production from a cascade bypassing the 125 μsec quasi-metastable state production (e.g., 31492.006.1)

3. Cascade gammas following quasi-metastable state ($T_{1/2}$<0.1 sec) production - This could be coded with a quasi-metastable state flag in SF4:

   Example (proposal):

   `82-PB-206(N,INL)82-PB-206-L,PAR,DA,DG`

   for the 803 keV gamma production following the 125 μsec quasi-metastable state production (e.g., 31492.006.2).



Appendix: Measurements of ^{206}Pb 803 keV γ production in EXFOR

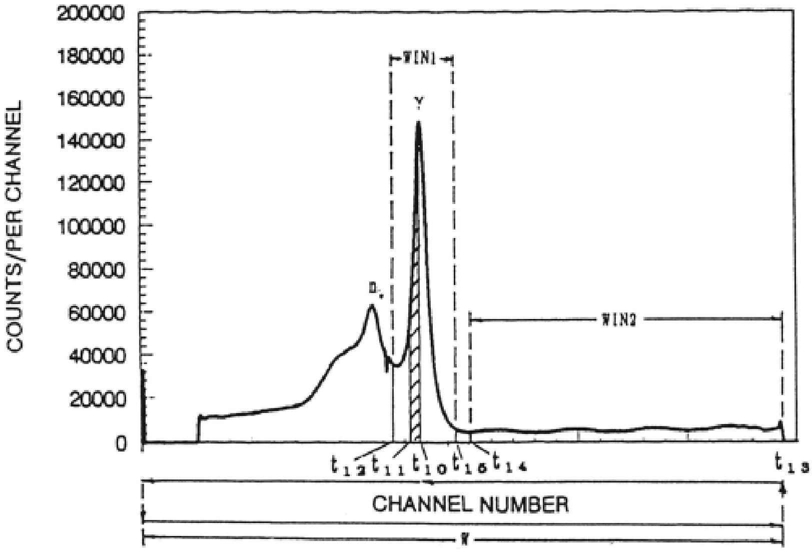
<u>“Prompt” and “delayed” components of the 803 keV γ line from Pb+n</u>

Below is a table providing gamma production cross secions from irradiation of natural Pb by 14.9 MeV neuttrons at Beijing Normal Unvieristy (Hongyu Zhou+, J,NSE,134,106,2000, EXFOR 31492).

E_γ (keV)	Final Nucleus	Transition (keV)	$t_{1/2}$	Elemental Cross Sectio		
				Present Work		
				55 deg	90 deg	140 deg
343.3	^{206}Pb	1648.1 to 1340.6	Prompt	1.27 ± 0.38	1.47 ± 0.34	1.11 ± 0.33
343.3	^{206}Pb	1648.1 to 1340.6	124 μs	5.63 ± 1.13	3.94 ± 1.58	4.10 ± 1.64
458.1	^{206}Pb	2658.5 to 2200.2	Prompt	2.86 ± 0.28	2.45 ± 0.34	2.74 ± 0.21
516.4	^{206}Pb	2200.2 to 1684.1	124 μs	20.5 ± 1.0	21.0 ± 1.0	19.9 ± 1.5
537.3	^{206}Pb	1340.6 to 803.1	Prompt	10.2 ± 0.5	9.82 ± 0.40	10.2 ± 0.6
537.3	^{206}Pb	1340.6 to 803.1	124 μs	6.24 ± 0.50	5.70 ± 0.54	6.29 ± 0.60
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
570.0	^{207}Pb	570.0 to 0	0.81 s	49.0 ± 1.5	48.7 ± 1.5	48.9 ± 1.5
583.2	^{208}Pb	3197.7 to 2614.5	Prompt	8.20 ± 0.41	7.15 ± 0.36	7.44 ± 0.47
656.8	^{207}Pb	3384.0 to 2728.0	Prompt	4.17 ± 0.17	3.73 ± 0.13	4.10 ± 0.19
	^{206}Pb	1997.8 to 1340.6				
663.9	^{206}Pb	1466.6 to 803.1	Prompt	2.99 ± 0.13	2.54 ± 0.24	3.08 ± 0.14
675.7	^{207}Pb	3300.0 to 2624.0	Prompt	1.74 ± 0.35	1.38 ± 0.27	1.52 ± 0.30
683.6	^{205}Pb	1697.2 to 1013.8	Prompt	4.66 ± 0.47	3.72 ± 0.37	3.98 ± 0.40
703.4	^{205}Pb	2203.9 to 1705.0	Prompt	6.07 ± 0.25	5.98 ± 0.33	5.74 ± 0.42
744.9	^{205}Pb	1758.5 to 1013.7	Prompt	1.06 ± 0.22	1.16 ± 0.14	1.31 ± 0.23
761.4	^{207}Pb	3384.0 to 2624.0	Prompt	2.06 ±0.21	2.34 ± 0.23	1.96 ± 0.34
781.7	^{207}Pb	3509.0 to 2728.0	Prompt	1.08 ± 0.20	1.87 ± 0.48	1.76 ± 0.32
802.9	^{206}Pb	803.0 to 0	Prompt	29.1 ± 0.90	24.71 ± 0.80	25.5 ± 1.0
802.9	^{206}Pb	803.0 to 0	124 μs	19.9 ± 0.8	19.3 ± 0.6	19.1 ± 0.8
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
880.9	^{206}Pb	1684.0 to 803.0	Prompt	5.99 ± 0.36	4.85 ± 0.34	5.24 ± 0.37
880.9	^{206}Pb	1684.0 to 803.0	124 μs	13.2 ± 0.8	13.4 ± 0.5	14.2 ± 0.8

The authors report two components (“prompt” and “124 μsec”) for several ^{206}Pb gamma lines (*e.g.*, 803 keV $2^+ \rightarrow 0^+$ γ line). The “delayed” component is originated from gamma cascades through the 125 μsec quasi-metastable state at 2200 keV.

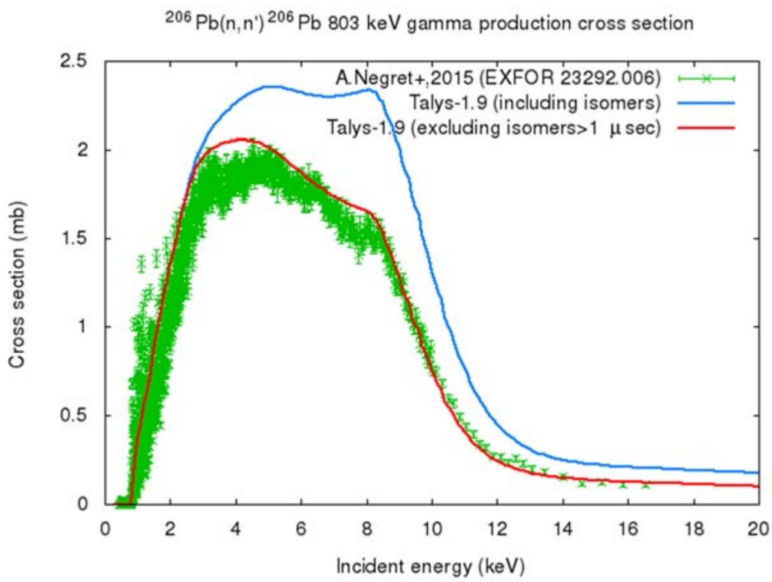
Their preceding article Hongyu Zho+,J,NSE,125,61,1997 (EXFOR 31528) shows a TOF-γ spectrum with two time windows – “WIN1” (30 nsec) for total “prompt” gamma + partial “delayed” gamma, and “WIN2” (160 nsec) for partial “delayed” gamma. The same spectrum and more technical details are published in Hongyu Zho+,J,NIM/A,371,504,1996.



Namely, a measurement with fast timing may report only the “prompt” portion of the γ production cross sections. The Pb+n γ production cross section measurement at GELINA and published in A.Negret+,J,PR/C,91,064618,2015 (EXFOR 23292) is such an example. It mentions:

> “The second limitation concerns an isomer at 2200.2 keV with a lifetime of 180(3) μs. The γ rays from the decay of this isomer (516.2 and 202.4 keV) are delayed and almost all of the decay occurs outside of the 24-μs time span of the present measurement. Therefore the **γ rays emitted following the decay of the isomer are hard to observ**e and…”

Indeed Talys-1.9 reproduces their experimental 803 keV gamma production cross sections (EXFOR 23292.006) if we exclude contribution of the gammas originating from the cascades through the quasi-metastable state.



Comparison of production cross sections compiled from various articles

This implies datasets coded with `(82-PB-206(N,INL)82-PB-206,PAR,DA,G)` are not always comparable each other. Hongyu Zhou+,J,NSE,125,61,1997 (EXFOR 31528) mentions that:

> "… **different experimental methods can give different results.** For example, the associated-particle method can give only the pure prompt component data. The pulsed-beam method can also produce different results because of different parameters sets used and different data reduction methods".

Table collects the 803 keV γ-ray production cross sections. "prompt" and "delayed" are in terms of the half-life of 125 μsec quasi-metastable state, and only the 31492 article gives two components separately. Note that NaI has poor energy resolution, and it has more probability to detect some gamma lines unresolved from the 803 keV gamma line.

Table

Pb(n,γ+x) 803 keV (IT decay of 125 μsec ^{206}Pb may contribute to the delayed portion)

EXFOR #	Year	θ (deg)	En (MeV)	dσ/dΩ (mb/sr)	Remark
20164.057	1969	80	14.7	42(2)	GeLi
23341.026	1991	90	13.0	24.7(35)	NaI+TOF
13034.009	1972	90	14.4	47(8)	NaI
31492.006.1	2000	90	14.9	19.3(8)	GeLi+TOF, delayed
31492.006.2	2000	90	14.9	24.7(8)	GeLi+TOF, prompt
21304.029	1978	125	14.8	69.1(75)	GeLi
31492.006.1	2000	140	14.9	19.1(8)	GeLi+TOF, delayed
31492.006.2	2000	140	14.9	25.5(10)	GeLi+TOF, prompt

Experimental aspects

Some comments received from experts are collected below. I feel we should be careful when there is a level having a micro-sec order half-life.

- Nowadays it is common to uses fast timing / time gating with typical time resolution of ~30 nsec with old electronics or ~10 nsec with new electronics.

- In 1970s, the importance of the fast timing becomes apparent, and hardware became available.

- HPGe, GeLi and NaI have the time resolution of ~10 nsec or more (which is longer than the beam width). γ -flash gate window is set several times longer, but it is still in order of 100 ns. Namely the cascade following transition from a level with $T_{1/2}$~100 nsec or longer is not excluded.

- For ^{48}Ti(n,n'γ)^{48}Ti datasets (c.f. INDC(NDS)-0740), only around half of the measurements employed TOF to separate secondary gammas originated from background neutrons.

- There could be an impact of an isomer on a neutron capture cross section measurement with the pulse height weighting technique (PHWT) if the position of the isomer is comparable with the neutron binding energy of the compound nuclide B_n (N.B. The capture yield is determined by PHWT by $Y=\Sigma_i$ $[S_iW_i/(Bn+En)]$ where S_i is the pulse height of the i-th γ line and W_i is the weighting function.

Memo CP-D/1073

Memo CP-D/1057 discusses the gamma production following quasi-metastable state production.

1. Cascade gammas not following quasi-metastable state (“prompt” component)
2. Cascade gammas following quasi-metastable state (“delayed” component)

The following new codes are proposed:

Dictionary 236 (Quantities)

PAR/L-,DA,G Angular distribution of prompt discrete gamma ray transition, excluding formation via quasi-metastable state.

Dictionary 31 (Branches)

L- Excluding formation via quasi-metastable state production.

Coding sample (H.Zhou et al.,J,NSE,134,106,2000):

```
SUBENT        31492002   20021018   20021204   20050926       0000
BIB                  3          4
REACTION  1(82-PB-0(N,X)82-PB-206,PAR/L-,DA,G) Prompt.
          2(82-PB-0(N,X)82-PB-206-L,PAR,DA,DG) Delayed.
DECAY-DATA (82-PB-206-M,.124MSEC,DG,343.3)
ENDBIB               4
COMMON               3          3
E          LVL-INI    LVL-FIN
KEV        KEV        KEV
343.3      1684.1     1340.6
ENDCOMMON            3
DATA                 5          3
ANG        DATA      1DATA-ERR  1DATA      2DATA-ERR  2
ADEG       MB/SR      MB/SR      MB/SR      MB/SR
55.        1.27       .38        5.63       1.13
90.        1.47       .34        3.94       1.58
140.       1.11       .33        4.10       1.64
ENDDATA              5
ENDSUBENT           18
```