



Fig. 1: Known experimental values for heavy particle emission of the even-Z  $T_z = +22$  nuclei.

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**Table 1**

Observed and predicted  $\beta$ -delayed particle emission from the even- $Z$ ,  $T_z = +22$  nuclei.  $J^\pi$  values for  $^{204}\text{Tl}$  and  $^{208}\text{Bi}$  are taken from ENSDF. Unless otherwise stated, all  $Q$ -values are taken from [2021Wa16] or deduced from values therein.

| Nuclide                  | Ex.        | $J^\pi$  | $T_{1/2}$           | $Q_\epsilon$ | $Q_{\epsilon p}$ | $Q_{\epsilon\alpha}$ | Experimental         |
|--------------------------|------------|----------|---------------------|--------------|------------------|----------------------|----------------------|
| $^{208}\text{Pb}$        |            | $0^+$    | stable              | -4.999(2)    | —                | —                    |                      |
| $^{212}\text{Po}$ (ThC') |            | $0^+$    | 294.965(178) ns     | -2.252(2)    | —                | —                    | [2022Be20]           |
| $^{212m1}\text{Po}$      | 1.4764(2)* | $(8^+)$  | 17.1(2) ns          | -0.776(2)    | —                | —                    | [1978Li14]           |
| $^{212m2}\text{Po}$      | 2.930(10)* | $(18^+)$ | 45.1(6) s           | 0.678(2)     | -4.235(2)        | 6.886(2)             | [1962Pe15]           |
| $^{216}\text{Rn}$        |            | $0^+$    | 29(4) $\mu\text{s}$ | -2.003(7)    | —                | —                    | [2018Sa45]           |
| $^{220}\text{Ra}$        |            | $0^+$    | 18(2) ms            | -1.210(8)    | —                | —                    | [2000He17]           |
| $^{224}\text{Th}$        |            | $0^+$    | 1.05(2) s           | -0.239(10)   | —                | —                    | [1978IbZZ]           |
| $^{228}\text{U}$         |            | $0^+$    | 9.1(2) m            | 0.296(14)    | -3.874(14)       | 6.561(14)            | [1961Ru06]           |
| $^{232}\text{Pu}$        |            | $0^+$    | 33.7(5) m           | 1.00(10)#    | -2.734(17)#      | 7.012(17)#           | [2000La25, 1973Ja06] |
| $^{236}\text{Cm}$        |            | $0^+$    | 410(50) s           | 1.81(12)#    | -1.618(27)       | 8.07(10)#            | [2010Kh06]           |
| $^{240}\text{Cf}$        |            | $0^+$    | 1.00(12) m***       | 2.32(15)#    | -0.45(15)#       | 9.52(12)#            | [1995La09, 1980Vi04] |
| $^{244}\text{Fm}$        |            | $0^+$    | 3.12(8) ms          | 2.94(27)#    | 0.69(27)#        | 10.88(25)#           | [2008Kh10]           |
| $^{248}\text{No}$        |            | $0^+$    |                     | 3.74(29)#    | 1.73(29)#        | 12.24(29)#           |                      |

\* [2020Au03].

\*\* Weighted average of 33.1(8) m [2000La25] and 34.1(7) m [1973Ja06].

\*\*\* Weighted average of 0.9(2) m [1995La09] and 1.06(15) m [1980Vi04].

**Table 2**

Particle separation,  $Q$ -values, and measured values for direct particle emission of the even- $Z$ ,  $T_z = +22$  nuclei. Unless otherwise stated, all  $S$  and  $Q$ -values are taken from [2021Wa16] or deduced from values therein.

| Nuclide                  | $S_p$     | $S_{2p}$   | $Q_\alpha$ | $BR_\alpha$     | $BR_{SF}$ | Experimental   |
|--------------------------|-----------|------------|------------|-----------------|-----------|--|
| $^{208}\text{Pb}$        | 8.003(5)  | 15.381(20) | 0.517(1)   |                 |           |  |
| $^{212}\text{Po}$ (ThC') | 5.799(5)  | 10.219(1)  | 8.9542(1)  | 100%            |           | [2023Sa32, 1991Ry01, 1974Hu15, 1971De52, 1971Gr17, 1961Ry02, 2022Be20, 2018Sa45, 2018So16, 2017Ap03, 2014Be39, 2013Be31, 2012Be14, 2003Da24, 2001MoZV, 1982Bo04, 1976GIZM, 1975Sa06, 1973BoXL, 1972RyZX, 1965Le08, 1960Em01, 1960Ha19, 1960Ry01, 1957Ec08, 1953Ha09, 1949Me54, 1949Va01, 1948Gh01, 1948Hi21, 1933Ro03, 1906Ha02] |
| $^{212m1}\text{Po}$      | 4.323(5)  | 8.743(1)   | 10.4306(2) | $\approx 42\%$  |           | [1984Es01, 1978Li14, 1979LiZP]   |
| $^{212m2}\text{Po}$      | 2.869(11) | 7.289(10)  | 11.884(10) | 99.93(2)%       |           | [1989Ku08, 1976FrZO, 1962Pe15]   |
| $^{216}\text{Rn}$        | 5.779(9)  | 9.855(6)   | 8.198(6)   | 100%            |           | [1970Va13, 2018Sa45, 1961Ru06, 1960Ru02, 1952Or03, 1949Me54]   |
| $^{220}\text{Ra}$        | 5.634(10) | 9.523(8)   | 7.594(5)   | 100%            |           | [1970Va13, 1961Ru06, 2018Sa45, 2000He17, 1990An19, 1990AnZQ, 1989An13, 1988AnZS, 1978IbZZ, 1952Or03, 1950OrZZ, 1949Me54]   |
| $^{224}\text{Th}$        | 5.118(12) | 8.903(10)  | 7.299(6)   | $\approx 100\%$ |           | [2000He17, 1970Va13, 1961Ru06, 1989An13, 1988AnZS, 1978IbZZ, 1973ScXO, 1973ScXP, 1960Ru02, 1952Or03, 1949Me25]   |
| $^{228}\text{U}$         | 4.899(15) | 8.556(14)  | 6.800(9)   | $> 95\%$        |           | [1961Ru06, 1960Ru02, 1952Or03, 1951Me10, 1950OrZZ, 1949Me54]   |
| $^{232}\text{Pu}$        | 4.552(54) | 7.832(17)  | 6.716(10)  | $\leq 20\%$     |           | [1973Ja06, 2000La25, 1952Or03, 1950OrZZ]   |
| $^{236}\text{Cm}$        | 4.061(56) | 7.075(19)  | 7.067(5)   | 18(2)%          |           | [2010Kh06, 2010AsZX]   |
| $^{240}\text{Cf}$        | 3.55(21)# | 6.034(22)  | 7.711(4)   | 98.5(23)%       | 1.5(2)%   | [2010AsZX, 2010Kh06, 1995La09, 1980Vi04, 1970Si19]   |
| $^{244}\text{Fm}$        | 3.07(29)# | 5.00(20)#  | 8.55(20)#  | $< 1\%$         | $> 97\%$  | [2008Kh10, 2013SvZZ, 2012SvZZ, 1982Bo21, 1982BoZN, 1980Vi04, 1979Ga06, 1978GaZW, 1975Og02]   |
| $^{248}\text{No}$        | 2.54(31)# | 4.08(23)#  | 9.30(10)#  |                 |           |  |

**Table 3**

direct  $\alpha$  emission from  $^{212}\text{Po}$ ,  $J^\pi = 0^+$ ,  $T_{1/2} = 294.965(178)$  ns\*,  $BR_\alpha = 100\%$ .

| $E_\alpha$ (c.m.) | $E_\alpha$ (lab) | $I_\alpha$ (abs) | $J_f^\pi$ | $E_{daughter}$ ( $^{208}\text{Pb}$ ) | coincident $\gamma$ -rays | $R_0$ (fm)  | HF        |
|-------------------|------------------|------------------|-----------|--------------------------------------|---------------------------|-------------|-----------|
| 8.95380(12)       | 8.78486(12)**    | 100%             | $0^+$     | 0.0                                  | —                         | 1.52177(18) | 0.992(27) |

\* [2022Be20].

\*\* Value taken from [1991Ry01], based on adjusted values of 8784.90(12) keV [1974Hu15], 8784.37(7) keV [1972RyZX] and 8784.85(31) keV [1971De52].

**Table 4**direct  $\alpha$  emission from  $^{212m1}\text{Po}$ , Ex. = 1.4764(2) MeV\*,  $J^\pi = (8^+)$ ,  $T_{1/2} = 17.1(2)$  ns\*\*,  $BR_\alpha = \approx 42\%$ \*\*\*.

| $E_\alpha$ (c.m.) | $E_\alpha$ (lab) | $I_\alpha$ (abs)   | $J_f^\pi$ | $E_{daughter}(^{208}\text{Pb})$ | coincident $\gamma$ -rays | $R_0$ (fm)  | HF            |
|-------------------|------------------|--------------------|-----------|---------------------------------|---------------------------|-------------|---------------|
| 10.376(30)        | 10.180(30)**     | $\approx 42\%$ *** | $0^+$     | 0.0                             | —                         | 1.52177(18) | $\approx 124$ |

\* [2020Au03].  
\*\* [1978Li14].  
\*\*\* [1984Es01].

**Table 5**direct  $\alpha$  emission from  $^{212m2}\text{Po}$ \*, Ex. = 2.930(10) MeV\*\*,  $J^\pi = (18^+)$ ,  $T_{1/2} = 45.1(6)$  s\*\*\*,  $BR_\alpha = 99.93(2)\%$ @.

| $E_\alpha$ (c.m.) | $E_\alpha$ (lab) | $I_\alpha$ (rel) | $I_\alpha$ (abs) | $J_f^\pi$ | $E_{daughter}(^{208}\text{Pb})$ | coincident $\gamma$ -rays | $R_0$ (fm)  | HF  |
|-------------------|------------------|------------------|------------------|-----------|---------------------------------|---------------------------|-------------|---|
| 8.689(8)          | 8.525(8)         | 100%             | 96.8%            | $5^-$     | 3.195(13)                       | 0.570, 2.614              | 1.52177(18) | $3.6(4) \times 10^7$  |
| 9.270(10)         | 9.095(10)        | 1.2(2)%          |                  | 1.2(2)%   | $3^-$                           | 2.614(14)                 | 2.614       | 1.52177(18)   |
| 11.884(10)        | 11.660(10)       | 2.1(3)%          | 2.1(3)%          |           | $0^+$                           | 0.0                       | —           | $6.7_{-1.2}^{+1.6} \times 10^{10}$<br>$1.9(3) \times 10^{15}$ |

\* All values from [1976FrZO], except where noted.  
\*\* [2020Au03].  
\*\*\* [1962Pe15].  
@ [1989Ku08].

**Table 6**direct  $\alpha$  emission from  $^{216}\text{Rn}$ ,  $J^\pi = 0^+$ ,  $T_{1/2} = 45(5)$   $\mu\text{s}$ \*,  $BR_\alpha = 100\%$ .

| $E_\alpha$ (c.m.) | $E_\alpha$ (lab) | $I_\alpha$ (abs) | $J_f^\pi$ | $E_{daughter}(^{212}\text{Po})$ | coincident $\gamma$ -rays | $R_0$ (fm) | HF       |
|-------------------|------------------|------------------|-----------|---------------------------------|---------------------------|------------|----------|
| 8.202(10)         | 8.050(10)**      | 100%             | $0^+$     | 0.0                             | —                         | 1.5658(59) | 1.03(12) |

\* [1961Ru06].  
\*\* [1970Va13].

**Table 7**direct  $\alpha$  emission from  $^{220}\text{Ra}$ ,  $J^\pi = 0^+$ ,  $T_{1/2} = 18(2)$  ms\*,  $BR_\alpha = 100\%$ .

| $E_\alpha$ (c.m.) | $E_\alpha$ (lab)** | $I_\alpha$ (rel) | $I_\alpha$ (abs) | $J_f^\pi$ | $E_{daughter}(^{216}\text{Rn})$ | coincident $\gamma$ -rays | $R_0$ (fm) | HF                  |
|-------------------|--------------------|------------------|------------------|-----------|---------------------------------|---------------------------|------------|---------------------|
| 7.03              | 6.90               | 1.0(4)%          | 1.0(4)%          | $2^+$     | 0.461(2)@                       | 0.4614(2)@                | 1.5539(57) | $2.6_{-1.0}^{+2.3}$ |
| 7.591(7)          | 7.453(7)***        | 100%             | 99%              | $0^+$     | 0.0                             | —                         | 1.5539(57) | 0.99(11)            |

\* [2000He17].  
\*\* In addition to those listed, [2000He17] reported a 5(3)% 7393(15) MeV  $\alpha$  transition to a state at 58(18) keV in  $^{216}\text{Rn}$ , which would be very unlikely in this nucleus.  
\*\*\* Weighted average of 7.455(10) MeV [1970Va13] and 7.450(10) MeV [1961Ru06].  
@ [2007Wu02].

**Table 8**direct  $\alpha$  emission from  $^{224}\text{Th}$ ,  $J^\pi = 0^+$ ,  $T_{1/2} = 1.05(2)$  s\*,  $BR_\alpha = \approx 100\%$ .

| $E_\alpha$ (c.m.) | $E_\alpha$ (lab) | $I_\alpha$ (rel) | $I_\alpha$ (abs) | $J_f^\pi$ | $E_{daughter}(^{220}\text{Ra})$ @ | coincident $\gamma$ -rays@ | $R_0$ (fm) | HF                     |
|-------------------|------------------|------------------|------------------|-----------|-----------------------------------|----------------------------|------------|------------------------|
| 6.82              | 6.70             | 0.6(4)%          | 0.5(3)%          | $(3^-)$   | 0.474(2)                          | 0.1784(2), 0.2957(2)       | 1.5385(27) | $3_{-1}^{+4}$          |
| 6.89              | 6.77             | 1.9(8)%          | 1.5(6)%          | $4^+$     | 0.4101(2)                         | 0.1784(2), 0.2316(2)       | 1.5385(27) | $1.5_{-0.5}^{+1.1}$    |
| 7.122(8)          | 6.995(8)**       | 24(3)%           | 19(2)%           | $2^+$     | 0.1784(2)                         | 0.1784(2)                  | 1.5385(27) | $0.91_{-0.10}^{+0.13}$ |
| 7.293(7)          | 7.163(7)***      | 100%             | 79(2)%           | $0^+$     | 0.0                               | —                          | 1.5385(27) | 0.962(31)              |

\* [1978IbZZ].  
\*\* Weighted average of 6.984(15) MeV [2000He17] and 7.000(10) MeV [1970Va13].  
\*\*\* Weighted average of 7.156(10) MeV [2000He17] and 7.170(10) MeV [1970Va13].  
@ [2011Br05].

**Table 9**  
direct  $\alpha$  emission from  $^{228}\text{U}$ ,  $J^\pi = 0^+$ ,  $T_{1/2} = 9.1(2)$  m\*,  $BR_\alpha = > 95\%$ .

| $E_\alpha$ (c.m.) | $E_\alpha$ (lab) | $I_\alpha$ (rel) | $I_\alpha$ (abs) | $J_f^\pi$         | $E_{daughter}(^{224}\text{Th})^{**}$ | coincident $\gamma$ -rays**    | $R_0$ (fm) | HF                     |
|-------------------|------------------|------------------|------------------|-------------------|--------------------------------------|--------------------------------|------------|------------------------|
| 6.514             | 6.400            | 0.7(2)%          | 0.5(2)%          | 4 <sup>+</sup>    | 0.2841(5)                            | 0.0981(3), 0.1860(3)           | 1.5237(51) | $9_{-3}^{+6}$          |
| 6.555             | 6.440            | 1.0(4)%          | 0.7(3)%          | (1 <sup>-</sup> ) | 0.2510(3)                            | 0.0981(3), 0.1529(3), 0.246(3) | 1.5237(51) | $9_{-3}^{+7}$          |
| 6.708             | 6.590            | 41(8)%           | 29(4)%           | 2 <sup>+</sup>    | 0.0981(3)                            | 0.0981(3)                      | 1.5237(51) | $0.94_{-0.16}^{+0.21}$ |
| 6.799(10)         | 6.680(10)        | 100(6)%          | 70(4)%           | 0 <sup>+</sup>    | 0.0                                  | —                              | 1.5237(51) | 0.98(8)                |

\* All values from [1961Ru06], except where noted.  
\*\* [1991Sc08].

**Table 10**  
direct  $\alpha$  emission from  $^{232}\text{Pu}$ \*,  $J^\pi = 0^+$ ,  $T_{1/2} = 33.7(5)$  m\*\*,  $BR_\alpha = \leq 20\%$ .

| $E_\alpha$ (c.m.) | $E_\alpha$ (lab) | $I_\alpha$ (rel) | $I_\alpha$ (abs) | $J_f^\pi$      | $E_{daughter}(^{228}\text{U})$ | coincident $\gamma$ -rays | $R_0$ (fm) | HF    |
|-------------------|------------------|------------------|------------------|----------------|--------------------------------|---------------------------|------------|-------|
| 6.657(10)         | 6.542(10)        | 61%              | $\leq 7.6\%$     | 2 <sup>+</sup> | 0.059(14)                      | 0.059(14)                 | 1.487(50)  | >0.55 |
| 6.716(10)         | 6.600(10)        | 100%             | $\leq 12.4\%$    | 0 <sup>+</sup> | 0.0                            | —                         | 1.487(50)  | >0.60 |

\* All values from [1973Ja06], except where noted.  
\*\* Weighted average of 33.1(8) m [2000La25] and 34.1(7) m [1973Ja06].

**Table 11**  
direct  $\alpha$  emission from  $^{236}\text{Cm}$ ,  $J^\pi = 0^+$ ,  $T_{1/2} = 410(50)$  s\*,  $BR_\alpha = 18(2)\%$ .

| $E_\alpha$ (c.m.) | $E_\alpha$ (lab) | $I_\alpha$ (rel)     | $I_\alpha$ (abs) | $J_f^\pi$      | $E_{daughter}(^{232}\text{Pu})$ | coincident $\gamma$ -rays | $R_0$ (fm) | HF            |
|-------------------|------------------|----------------------|------------------|----------------|---------------------------------|---------------------------|------------|---------------|
| 7.013(5)          | 6.894(5)**       | $\approx 25\%^{***}$ | $\approx 4\%$    | 2 <sup>+</sup> | 0.054(7)                        | 0.054(7)                  | 1.5181(67) | $\approx 2.4$ |
| 7.067(5)          | 6.894(5)**       | 100%***              | $\approx 14\%$   | 0 <sup>+</sup> | 0.0                             | —                         | 1.5181(67) | $\approx 1.0$ |

\* [2010Kh06].  
\*\* [2010AsZX].  
\*\*\* Estimated by evaluator based on Fig 1b in [2010AsZX].

**Table 12**  
direct  $\alpha$  emission from  $^{240}\text{Cf}$ ,  $J^\pi = 0^+$ ,  $T_{1/2} = 1.00(12)$  m\*,  $BR_\alpha = 98.5(23)\%^{**}$ .

| $E_\alpha$ (c.m.) | $E_\alpha$ (lab) | $I_\alpha$ (rel)     | $I_\alpha$ (abs) | $J_f^\pi$      | $E_{daughter}(^{236}\text{Cm})$ | coincident $\gamma$ -rays | $R_0$ (fm) | HF            |
|-------------------|------------------|----------------------|------------------|----------------|---------------------------------|---------------------------|------------|---------------|
| 7.663(4)          | 7.535(4)**       | $\approx 33\%^{***}$ | $\approx 25\%$   | 2 <sup>+</sup> | 0.054(7)                        | 0.046(6)                  | 1.5027(72) | $\approx 1.9$ |
| 7.709(4)          | 7.581(4)**       | 100%***              | $\approx 75\%$   | 0 <sup>+</sup> | 0.0                             | —                         | 1.5027(72) | $\approx 0.9$ |

\* Weighted average of 0.9(2) m [1995La09] and 1.06(15) m [1980Vi04].  
\*\* [2010Kh06].  
\*\* [2010AsZX].

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