Section 8

NUCLEAR PHYSICS

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CONTENTS

8a. Nuclear Constants and Calibrations

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This section collects the various nuclear quantities that are useful in designing or analyzing experiments in nuclear physics. For an extensive collection of graphs and tables, the reader is directed to Marion and Young [1].

8a-1. Nuclear Constants in the MeV System. A complete list of fundamental physical constants and derived quantities is to be found inside the front cover of this volume. For many nuclear physics calculations, however, it is convenient to have certain of these quantities already expressed in MeV energy units. The following list has been generated by using the fundamental constants of Taylor, Parker, and Langenberg [2].

$$
\begin{aligned}
m_0c^2 &= 0.5110043 \text{ MeV}\\
M_pc^2 &= 938.2595 \text{ MeV}\\
M_nc^2 &= 939.5529 \text{ MeV}\\
c^2 &= 931.481 \text{ MeV/amu}\\
h &= 4.135705 \times 10^{-21} \text{ MeV-sec}\\
\hbar &= 6.582180 \times 10^{-22} \text{ MeV-sec}\\
\hbar c &= 1.973288 \times 10^{-11} \text{ MeV-cm}\\
\hbar^2c^2 &= 389.387 \text{ MeV}^2\text{-barn}\\
e &= 3.794703 \times 10^{-7} (\text{MeV-cm})^{\frac{1}{2}}\\
e^2 &= 1.439977 \times 10^{-13} \text{ MeV-cm}\\
e/\hbar c &= 1.923036 \times 10^{4} (\text{MeV-cm})^{-\frac{1}{2}}\\
(e/\hbar c)^2 &= 3.698066 \times 10^{8} (\text{MeV-cm})^{-1}\\
\hbar/m_0c^2 &= 1.288087 \times 10^{-21} \text{ sec}
\end{aligned}
$$

8a-2. Natural Units. If $\hbar = 1$ and $c = 1$, then

Mass, energy, and impulse are in units of cm^{-1}
Angular momentum is dimensionless
$e = 1/\sqrt{137}$
1 MeV = 0.506×10^{11} cm^{-1}

If $\hbar = 1$, $c = 1$, and $m_0 = 1$, then
1 sec = 7.764×10^{20} natural units
1 cm = 2.58×10^{10} natural units
1 MeV = 1.96 natural units

8a-3. Alpha-particle Calibration Energies. Listed in Table 8a-1 are the values for alpha-particle momenta and energies recommended by Wapstra [3]. The energies have been calculated for Wapstra's $B\rho$ values by using the expression

$$E = a(B\rho)^2 + b(B\rho)^4 + c(B\rho)^6$$

where a, b, and c are [1]

$$a = 48225.33 \times 10^{-12} \text{ keV (G-cm)}^{-2}$$
$$b = -311.98 \times 10^{-24} \text{ keV (G-cm)}^{-4}$$
$$c = 4.04 \times 10^{-36} \text{ keV (G-cm)}^{-6}$$

TABLE 8a-1. ALPHA-PARTICLE CALIBRATION ENERGIES

Source	$B\rho$, G-cm	Energy, keV
Po^{210}	331,722 ± 15	5304.5 ± 0.5
Bi^{211}	370,720 ± 40	6621.9 ± 1.4
Po^{211}	393,190 ± 50	7448.1 ± 1.9
Bi^{212}(ThC α_0)*	354,326 ± 20	6049.6 ± 0.7
Bi^{212}(ThC α_1)*	355,475 ± 20	6088.9 ± 0.7
Po^{212}(ThC′)	427,060 ± 20	8785.0 ± 0.8
Bi^{214}	338,170 ± 70	5510.9 ± 2.3
Po^{214}	399,488 ± 16	7688.4 ± 0.6
Po^{215}	391,490 ± 40	7383.9 ± 1.5
Po^{216}	375,050 ± 40	6777.3 ± 1.5
Po^{218}	352,870 ± 70	6000.1 ± 2.4
Rn^{219}	376,160 ± 40	6817.5 ± 1.5
Rn^{220}	361,260 ± 60	6288.5 ± 2.1
Rn^{222}	337,410 ± 70	5486.2 ± 2.3
Ra^{223}	349,010 ± 50	5869.6 ± 1.7
Ra^{224}	343,450 ± 40	5684.2 ± 1.3
Ra^{226}	314,990 ± 80	4781.8 ± 2.4
Th^{227}	354,070 ± 60	6040.9 ± 2.0
Th^{228}	335,570 ± 60	5426.6 ± 2.0
Th^{230}	311,960 ± 160	4690.3 ± 4.8

* Intensity ratio: $\alpha_0/\alpha_1 = 2.57$.

8a-4. Gamma-ray Calibration Energies. Listed in Tables 8a-2 to 8a-4 are the weighted mean values of the energies of gamma rays frequently used as calibration standards [4]. (A more comprehensive list may be found in ref. 4.) Also, relative intensities are given for Co^{56} since the gamma rays from this nucleus span such a wide energy range and are therefore of great value for both energy and efficiency calibrations. Gamma rays from both radioactive sources and nuclear reactions are given.

8a-5. Accelerator-energy Calibration Points. In order to know with precision the energy of the beam from an accelerator, unless an absolute instrument of some type is available, the beam-analyzing system must be calibrated against some accurately known energy points. One method frequently used to calibrate such analyzers is to measure a number of gamma-ray resonances and neutron thresholds to establish several points of the energy scale. Listed in Tables 8a-5 to 8a-7 are a number of energy points suitable for calibration purposes. Only the weighted mean values are given; more complete details can be found elsewhere [5].

TABLE 8a-2. GAMMA RAYS FROM RADIOACTIVE SOURCES

Source	Energy, keV	Half life	Source	Energy, keV	Half life
m_0c^2	511.006 ± 0.002		Cs^{137}	661.635 ± 0.076	30 y
Be^7	477.57 ± 0.05	53 d	Au^{198}	411.795 ± 0.009	2.70 d
Na^{22}	1274.55 ± 0.04	2.60 y	Bi^{207}	569.62 ± 0.06 1063.44 ± 0.09 1769.71 ± 0.13	30 y
Na^{24}	1368.526 ± 0.044 2753.92 ± 0.12	15.0 h	Tl^{208} (ThC″)	510.723 ± 0.020 583.139 ± 0.023 2614.47 ± 0.10	(1.91 y)
Cr^{51}	320.080 ± 0.013	27.8 d	Am^{241}	26.348 ± 0.010 59.543 ± 0.015	433 y
Mn^{54}	834.81 ± 0.03	314 d			
Co^{60}	1173.23 ± 0.04 1332.49 ± 0.04	5.26 y			
Zn^{65}	1115.40 ± 0.12	246 d			
Y^{88}	898.04 ± 0.04 1836.13 ± 0.04	106.6 d			

TABLE 8a-3. GAMMA RAYS FROM Co^{56}

Energy, keV	Relative intensity	Energy, keV	Relative intensity
733.79 ± 0.19	0.1 ± 0.05	2015.49 ± 0.20	2.93 ± 0.16
787.92 ± 0.15	0.40 ± 0.11	2035.03 ± 0.12	7.33 ± 0.30
846.76 ± 0.05	100	2113.00 ± 0.10	0.37 ± 0.08
977.47 ± 0.13	1.52 ± 0.16	2598.80 ± 0.12	16.77 ± 0.57
1037.97 ± 0.07	13.02 ± 0.35	3009.99 ± 0.24	0.84 ± 0.16
1175.26 ± 0.13	1.86 ± 0.23	3202.25 ± 0.19	3.15 ± 0.16
1238.34 ± 0.09	69.35 ± 1.47	3253.82 ± 0.15	7.70 ± 0.34
1360.35 ± 0.09	4.38 ± 0.16	3273.38 ± 0.18	1.55 ± 0.11
1771.57 ± 0.10	15.30 ± 0.53	3452.18 ± 0.22	0.88 ± 0.10
1964.88 ± 0.45	0.72 ± 0.08	3548.11 ± 0.25	0.18 ± 0.10

TABLE 8a-4. GAMMA RAYS FROM NUCLEAR REACTIONS

Nucleus	γ-ray energy, keV	Nucleus	γ-ray energy, keV
F^{17}	495.33 ± 0.10	C^{13}	4945.46 ± 0.17[e]
F^{18}	658.75 ± 0.7[a]	N^{14}	5104.87 ± 0.18
O^{17}	870.81 ± 0.22	O^{15}	5240.53 ± 0.52
B^{12}	953.10 ± 0.60	N^{15}	5268.9 ± 0.2
B^{12}	1673.52 ± 0.60	N^{15}	5297.9 ± 0.2[g]
N^{14}	2312.68 ± 0.10[b]	O^{16}	6129.3 ± 0.4
Be^{10}	2589.9 ± 0.25[c]	Be^{10}	6809.4 ± 0.4[e]
N^{14}	2792.68 ± 0.15[d]	O^{16}	7117.02 ± 0.49
Be^{10}	3367.4 ± 0.2[e]	Pb^{209}	7367.5 ± 1[e]
C^{12}	4439.0 ± 0.2[f]	N^{14}	9173 ± 1[h]
		N^{15}	10829.2 ± 0.4[e]

[a] From 1.70-1.04 MeV decay.
[b] Doppler shifted unless formed in $O^{14}(\beta^+)N^{14}$.
[c] From 5.96–3.37 MeV decay (thermal neutron capture).
[d] From 5.10–2.31 MeV decay.
[e] From thermal neutron capture.
[f] Doppler shifted unless formed in $B^{12}(\beta^-)C^{12}$.
[g] Doppler shifted unless formed in $O^{15}(\beta^-)N^{15}$ or by thermal neutron capture.
[h] Calculated from $C^{13}(p,\gamma)N^{14}$ resonance energy (1747.6 ± 0.9 keV) and 1964 masses; value given for observation at 0 deg to beam direction.

TABLE 8a-5. PROTON RESONANCE ENERGIES

Reaction	E_R, keV	Γ, keV
$F^{19}(p,\alpha\gamma)O^{16}$	340.46 ± 0.04	2.4 ± 0.2
$F^{19}(p,\alpha\gamma)O^{16}$	872.11 ± 0.20	4.7 ± 0.2
$Al^{27}(p,\gamma)Si^{28}$	991.90 ± 0.04	0.10 ± 0.02
$C^{13}(p,\gamma)N^{14}$	1747.6 ± 0.9	0.077 ± 0.012
$O^{16}(p,p)O^{16}$	12714 ± 8[a]	<3
$C^{12}(p,p)C^{12}$	14233 ± 8	<1

[a] See ref. 6.

TABLE 8a-6. (p,n) THRESHOLD ENERGIES

Reaction	E_{th}, keV
$Li^7(p,n)Be^7$	1880.60 ± 0.07
$C^{13}(p,n)N^{13}$	3235.7 ± 0.7
$F^{19}(p,n)Ne^{19}$	4234.3 ± 0.8
$Al^{27}(p,n)Si^{27}$	5796.9 ± 3.8
$S^{34}(p,n)Cl^{34}$	6451.1 ± 4.5
$Ni^{60}(p,n)Cu^{60}$	7023.6 ± 3.9
$Fe^{54}(p,n)Co^{54}$	9202.7 ± 4.8
$Ni^{58}(p,n)Cu^{58}$	9515.2 ± 2.9
$C^{12}(p,n)N^{12}$	19684 ± 8

Other useful calibration points are:

$O^{16}(d,n)F^{17}$	E_{th} = 1829.2 ± 0.6 keV[a]
$Mg^{24}(\alpha,\gamma)Si^{28}$	E_R = 3200 ± 1 keV[b]

[a] See ref. 7.
[b] See ref. 8.

Threshold energies for various helium-ion-induced reactions can be calculated from the 1964 adjustment of atomic masses [9].

TABLE 8a-7. CALCULATED NEUTRON THRESHOLD ENERGIES

Reaction	E_{th}, MeV ± keV
$Li^6(He^3,n)B^8$	2.9650 ± 1.5
$Li^6(\alpha,n)B^9$	6.6239 ± 2.6
$Li^7(\alpha,n)B^{10}$	4.3843 ± 1.9
$C^{12}(He^3,n)O^{14}$	1.4366 ± 0.5
$C^{12}(\alpha,n)O^{15}$	11.3463 ± 1.7
$N^{14}(\alpha,n)F^{17}$	6.0888 ± 0.8
$N^{15}(\alpha,n)F^{18}$	8.1324 ± 1.5
$O^{16}(He^3,n)Ne^{18}$	3.7987 ± 5.7
$O^{16}(\alpha,n)Ne^{19}$	15.1761 ± 2.0

References

1. Marion, J. B., and F. C. Young: "Nuclear Reaction Analysis: Graphs and Tables," North-Holland, Publishing Company, Amsterdam, 1968.
2. Taylor, B. N., W. H. Parker, and D. N. Langenberg: *Rev. Mod. Phys.* **41,** 375 (1969).
3. Wapstra, A. H.: *Nucl. Phys.* **57,** 48 (1964).
4. Marion, J. B.: *Nucl. Data* **A4,** 301 (1968).
5. Marion, J. B.: *Rev. Mod. Phys.* **38,** 660 (1966).
6. Patterson, J. R., H. Winkler, and C. S. Zaidins: *Phys. Rev.* **163,** 1051 (1967).
7. Bondelid, R. O., J. W. Butler, and C. A. Kennedy: *Phys. Rev.* **120,** 889 (1960).
8. Rytz, A., H. Staub, H. Winkler, and F. Zamboni: *Nucl. Phys.* **43,** 229 (1963).
9. Mattauch, J. H. E., W. Thiele, and A. H. Wapstra: *Nucl. Phys.* **67,** 73 (1965).