A. Relativistic kinematics

In this appendix, we briefly review some facts from the special theory of relativity that are useful in nuclear physics. Relativity is used in nuclear physics primarily through the relativistic expressions for the energy and momentum of a free particle of (rest) mass m and velocity $\boldsymbol{v}$:

$$E = \frac{mc^2}{\sqrt{1-v^2/c^2}} \qquad \boldsymbol{p} = \frac{m\boldsymbol{v}}{\sqrt{1-v^2/c^2}} \; . \tag{A.1}$$

The energy and momentum defined in this way are conserved quantities. They satisfy

$$E^2 = m^2c^4 + p^2c^2 \qquad \frac{v}{c} = \frac{pc}{E} \; . \tag{A.2}$$

In nuclear physics, the non-relativistic limit $v \ll c$ ($\Rightarrow pc \ll E$) usually applies for nuclei, in which case we have

$$E \sim mc^2 + \frac{p^2}{2m} \qquad v = \frac{p}{m} \; . \tag{A.3}$$

For neutrinos and photons, the limit $mc \ll p$ generally applies:

$$E \sim pc + \frac{m^2c^2}{2p^2} \; . \qquad v = c\left(1 - \frac{m^2c^2}{2p^2}\right) \; . \tag{A.4}$$

It is customary to group energy and momentum in a single object called the energy-momentum *4-vector*

$$P \equiv (E, \boldsymbol{p}) \; . \tag{A.5}$$

In a particle's rest-frame, it takes the value $(mc^2, 0, 0, 0)$. The squared magnitude of the 4-vector is defined as

$$P^2 \equiv P \cdot P \equiv E^2 - \boldsymbol{p}\cdot\boldsymbol{p} = m^2c^4 \; , \tag{A.6}$$

where the last form follows from (A.1). The magnitude is clearly independent of the energy of the particle, i.e. it is invariant with respect to changes of reference frame.

Consider the energy-momentum of a particle, P, viewed in an inertial reference frame. Consider another inertial reference frame moving with velocity v in, say, the z direction with respect to the first. The energy-momentum

4-vector in the second is related to that in the first by a *Lorentz transformation*:

$$\begin{pmatrix} E' \\ p'_x c \\ p'_y c \\ p'_z c \end{pmatrix} = \begin{pmatrix} \gamma & 0 & 0 & -\beta\gamma \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\beta\gamma & 0 & 0 & \gamma \end{pmatrix} \begin{pmatrix} E \\ p_x \\ p_y \\ p_z \end{pmatrix} , \tag{A.7}$$

where

$$\beta = v/c \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}} . \tag{A.8}$$

The generalizations to other directions are obvious. This relation follows trivially from (A.1) if one of the frames is the rest-frame. It is less obvious in the general case but note that the transformation has the virtue of maintaining the magnitude (A.6), as it must.

Energy momentum conservation can be economically expressed by using 4-vectors. Consider the decay

$$A \rightarrow BC . \tag{A.9}$$

Energy-momentum conservation is

$$P_A = P_B + P_C , \tag{A.10}$$

which is entirely equivalent to

$$E_A = E_B + E_C \qquad \boldsymbol{p}_A = \boldsymbol{p}_B + \boldsymbol{p}_C . \tag{A.11}$$

One is often called upon to calculate the momentum of the decay products in the rest frame of the decaying particle ($\boldsymbol{p}_A = 0$). Momentum conservation gives $\boldsymbol{p}_B = -\boldsymbol{p}_C$ so energy conservation gives

$$m_A c^2 = \sqrt{p^2c^2 + m_B^2 c^4} + \sqrt{p^2c^2 + m_C^2 c^4} , \tag{A.12}$$

where p is the common momentum we would like to find. This equation is not especially easy to solve. It is much easier to write the 4-vector equation

$$P_C = P_A - P_B . \tag{A.13}$$

We now take the squared magnitude of both sides of this equation:

$$m_C^2 c^4 = (P_A - P_B)^2 = P_A^2 + P_B^2 - 2P_A \cdot P_B . \tag{A.14}$$

The first two terms on the right give $m_A^2 c^4 + m_B^2 c^4$. Since the scalar product $P_A \cdot P_B$ is Lorentz invariant, we can evaluate it in the rest frame of A:

$$P_A \cdot P_B \equiv E_A E_B - \boldsymbol{p}_A \cdot \boldsymbol{p}_B = m_A c^2 \sqrt{m_B^2 c^4 + p^2 c^2} . \tag{A.15}$$

We thus deduce

$$\sqrt{p^2c^2 + m_B^2 c^4} = \frac{m_A^2 c^4 + m_B^2 c^4 - m_C^2 c^4}{2 m_A c^2} , \tag{A.16}$$

$$p^2c^2 \;=\; \left(\frac{m_A^2c^4 + m_B^2c^4 - m_C^2c^4}{2m_Ac^2}\right)^2 \;-\; m_B^2c^4\;. \tag{A.17}$$

We note that in nuclear physics we can often use directly energy conservation (A.12) because all the particles are either ultra-relativistic or non-relativistic so we can eliminate the square roots. For example, in radiative decay of an excited nucleus

$$(A,Z)^* \;\rightarrow (A,Z)\,\gamma\,, \tag{A.18}$$

the two nuclei are non-relativistic so energy conservation is

$$m_*c^2 \;=\; mc^2 \,+\, \frac{p^2}{2m} \,+\, pc\,, \tag{A.19}$$

The nuclear kinetic energy is $pv/2 \ll pc$ so we have immediately

$$pc \;\sim\; (m_* - m)c^2\;. \tag{A.20}$$

This also follows from (A.17) in the limit $m_A^2 - m_C^2 \sim 2m_A(m_A - m_C)$ and $m_B = 0$.

B. Accelerators

The scattering experiments discussed in Chap. 3 generally required the use of beams of charged particles produced by accelerators. A notable exception is the original Rutherford-scattering experiments that used α-particles from natural radioactive decays. Neutron-scattering experiments use neutrons produced at fission reactors or secondary neutrons produced by the scattering of accelerated charged particles.

Particle accelerators require a source of charged particles and an electric field to accelerate them. They can be classified as *DC* machines using static electric fields and *AC* machines using oscillating fields. The second category can be divided into *linear accelerators* where particles are accelerated in straight line and *magnetic accelerators*, i.e. cyclotrons and synchrotrons, where particles move in circular orbits.

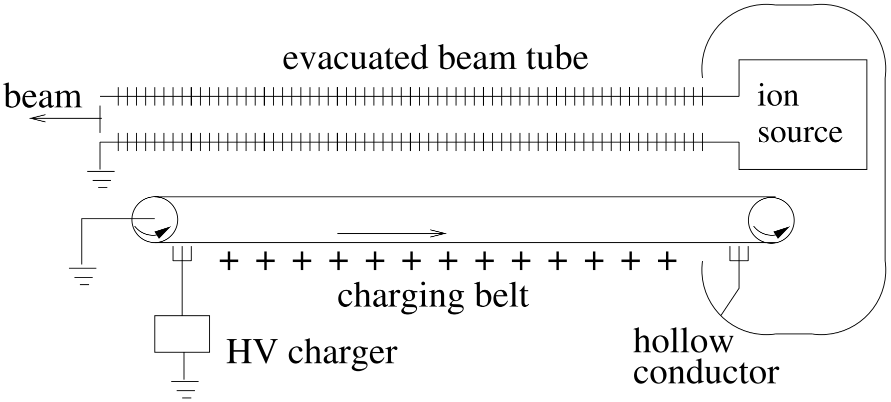

Fig. B.1. A schematic of a simple Van de Graff accelerator. Positive charges are transfered from ground potential to a hollow terminal. The ion source is placed inside the terminal and particles are accelerated through the electrostatic field to ground potential.

In simple electrostatic systems, an ion source is placed at high voltage and extracted ions are accelerated through the electric field. Potentials of $1-2\,\mathrm{MV}$ can be produced with normal rectifier circuits and potentials up to 10 MV can be produced in a *Van de Graff* accelerator, illustrated in Fig. B.1. In this system, charge is transformed to the positive terminal by an insulating belt. Ions are accelerated through an evacuated tube constructed from alternating insulators and electrodes so as to maintain a constant gradient. The maximum potential is limited by breakdown in the surrounding gas. Currents in the mA range can be achieved.

Tandem Van de Graff Accelerators (Fig. B.2) modify the basic design to provide higher energy and an ion source that is at ground potential, making it more accessible. In this case, the source provides singly-charged negative ions, e.g. O^- containing an extra electron. These are accelerating to the positive terminal where a "stripper" consisting of a thin foil or gas-containing tubes removes electrons. The resulting positive ions are then accelerated to ground potential where an analyzing magnet selects a particular value of q/m. Obtainable currents are in the μA range, smaller than simple Van de Graffs because of the difficulty in obtaining negative ions.

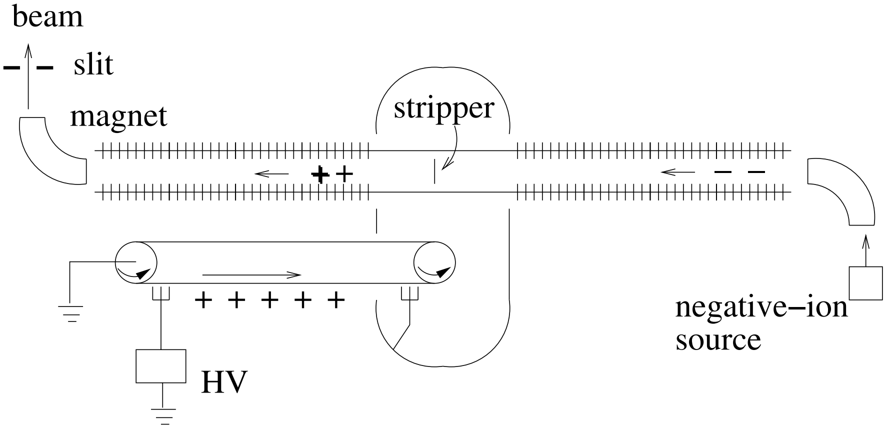

Fig. B.2. A schematic of a tandem Van de Graff accelerator. Negative ions are accelerated to the positive potential where a "stripper" removes electrons. The resulting positive ions are then accelerating to ground potential where a definite charge state is selected by a magnetic field and slit.

The 10 MV limitation of DC machines can be avoided by using radio-frequency (RF) electric fields. The frequency is typically ~ 30 MHz. The simplest configuration is the linear accelerator, or *linac*, illustrated in Fig. B.3. The RF voltage is applied to alternating conducting "drift tubes" so that charged particles are accelerating between tubes if they arrive at the gaps at appropriate times. The tube lengths must thus decrease in length as the particle velocity increases down the accelerator. Linacs produce a "bunched" beam consisting of pulses of particles. The bunch structure is persists during the acceleration because of the "phase stability" illustrated in Fig. B.4.

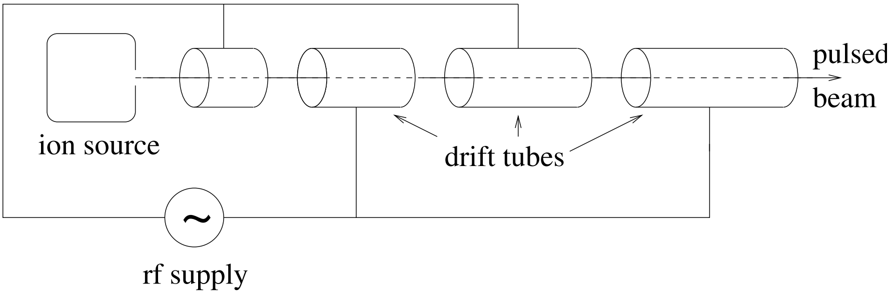

Fig. B.3. A schematic of a drift-tube linear accelerator. Ions are accelerated in the alternating electric field between drift-tubes.

Linear accelerators are most commonly used to accelerate electrons. The largest is the 2-mile long accelerating SLAC at Stanford, California, that produces 20 GeV electrons.

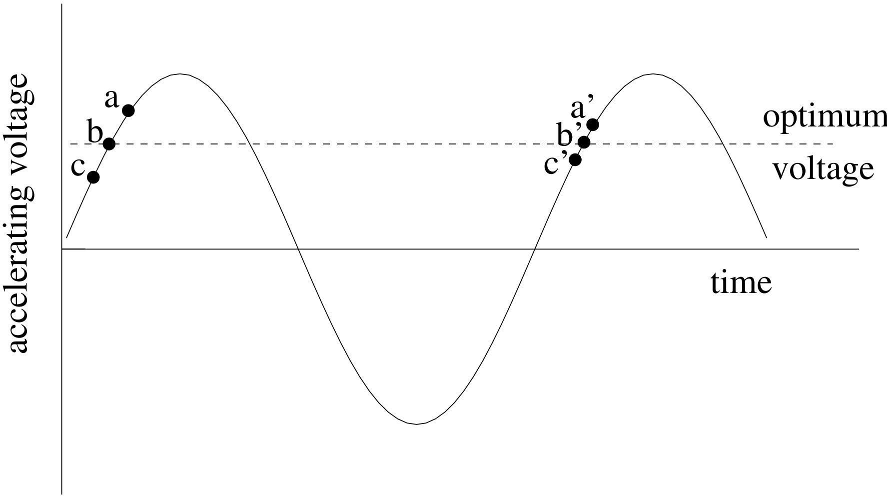

Fig. B.4. The principle of phase stability in a linear accelerator. Particles arriving in a gap at point b are accelerated such that they arrive at the text gap at the point b' with the same phase with respect to the alternating field. Particles arriving at point a (c) receive more (less) acceleration and therefore arrive relatively earlier (later) in the next gap, point a' (c'). Particles in the range a-c are thus "focused" in phase-space toward the point b.

Cyclotrons are a common class of accelerators illustrated in Fig. B.5. Ion orbit in a dipole magnetic field where they are accelerated twice per orbit in a RF field. As they are accelerated, the ions spiral out with the radius of curvature given by

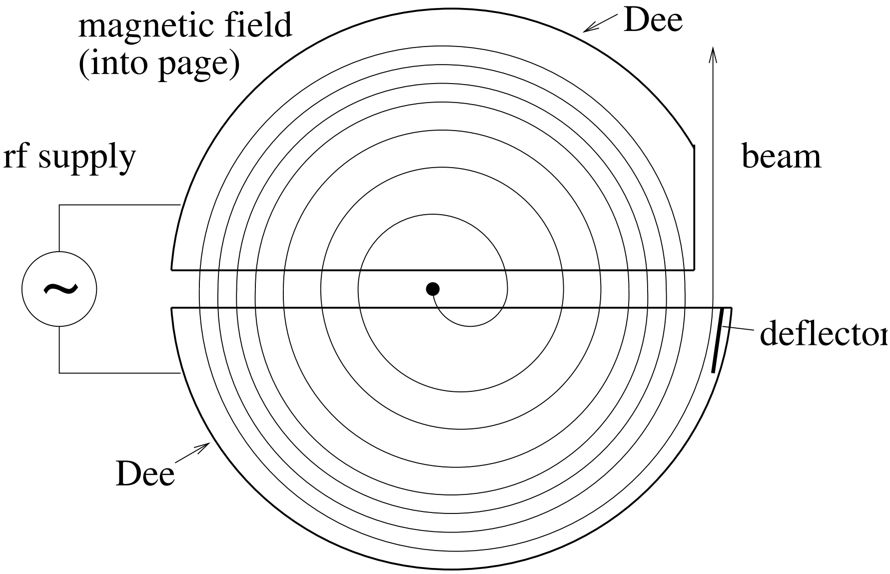

Fig. B.5. Schematic of a cyclotron. Particles are injected near the center of a dipole magnetic field and then spiral outward as they gain energy each time they pass through the alternating electric field between two electrodes called “Dee’s.” The radio-frequency is tuned to the particle’s cyclotron frequency, $\omega_{\mathrm{c}} = qB/m$. Near the maximum radius, the particles are deflected out of the cyclotron.

$$R = \frac{mv}{qB\sqrt{1-v^2/c^2}} , \tag{B.1}$$

for a particle of velocity v, mass m and charge q. The orbital frequency is then

$$f_{\mathrm{c}} = \frac{v}{2\pi R} = \frac{qB}{2\pi m}\sqrt{1-v^2/c^2} , \tag{B.2}$$

and the RF must be tuned to this frequency to accelerate the particles. As long as the particle remains non-relativistic, $v \ll c$, the frequency is a constant, proportional to the *cyclotron frequency*, qB/m, equal to $9.578 \times 10^7 \mathrm{rad\,s^{-1}\,T^{-1}} \times B$. The energy at radius R is, for $v \ll c$

$$\frac{1}{2}mv^2 = \frac{1}{2}m\left(\frac{qB}{m}\right)^2 R^2 \sim 10\,\mathrm{MeV}\left(\frac{B}{1\,\mathrm{T}}\right)^2\left(\frac{R}{0.5\,\mathrm{m}}\right)^2 , \tag{B.3}$$

where the numerical example is for a proton. A modest-sized cyclotron can therefore produce particles of energies interesting for nuclear-physics experiments. Currents in the mA range can be produced.

The simple design of a constant-field cyclotron must be modified in practical designs for a number of reasons. Most important is the necessity to prevent the particles from spiraling in the vertical direction. This can be prevented by introducing a small radial variation of the field, as illustrated in

Fig. B.6. This introduces vertical components to the force on particles that are not in the median plane so that particles are focused in the vertical direction. Unfortunately, this simple scheme introduces other problems, among them being that the required RF frequency now depends on position. More popular focusing schemes use magnetic fields that vary azimuthally to obtain the desired effect.

For energies $> 1\,\mathrm{GeV}$, cyclotrons become impractical because of the large required radius. It then becomes more practical to use *synchrotron's* where ring of dipole magnets replace the one large dipole. The accelerating force is provided by RF cavities distributed about the ring in spaces between magnets. Vertical and horizontal focusing is provided by quadrupole magnets. Sychrotrons are the most common accelerators in the field of high-energy particle physics.

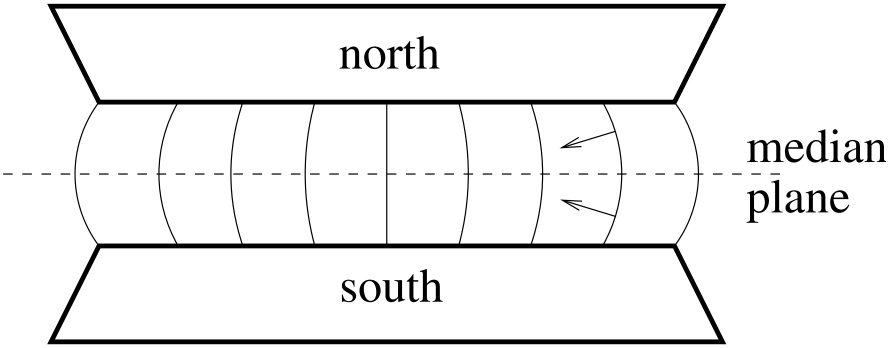

Fig. B.6. Vertical focusing in a radially-decreasing dipole magnetic field. Particles in the median plane experience a horizontal force. The force on particles above or below the median plane has a vertical component that pushes the particle back toward the median.

C. Time-dependent perturbation theory

Perturbation theory is the basis for most of the calculations performed in Chaps 3 and 4. Here we derive the basic equations.

C.0.1 Transition rates between two states

Consider a system described by a Hamiltonian H that is the sum of a "non-perturbed" Hamiltonian H_0 and a small perturbation H_1 which can induce transitions between various eigenstates of H_0. It is useful to express the state of the system as a superposition of eigenstates of H_0:

$$|\psi(t)\rangle \;=\; \sum_i \gamma_i(t)\mathrm{e}^{-\mathrm{i}E_i t/\hbar}|i\rangle \;, \tag{C.1}$$

where

$$H_0|i\rangle \;=\; E_i|i\rangle \;. \tag{C.2}$$

We suppose that the system is initially in the state $|i\rangle$:

$$\gamma_i(t=0) \;=\; 1 \qquad\qquad \gamma_{j\neq i}(0) \;=\; 0 \;. \tag{C.3}$$

At a later time, it has an amplitude $\gamma_f(t)$ to be in some other state $|f\rangle$. This amplitude can be calculated using the Schrödinger equation

$$i\hbar\frac{\mathrm{d}}{\mathrm{d}t}|\psi(t)\rangle \;=\; (H_0+H_1)|\psi(t)\rangle \;. \tag{C.4}$$

Substituting (C.1) into this equation, multiplying on the left by $\langle f|$ and using $\langle i|j\rangle = \delta_{ij}$, we find a differential equation for $\gamma_f(t)$:

$$i\hbar\frac{\mathrm{d}\gamma_f(t)}{\mathrm{d}t} \;=\; \sum_k \gamma_k(t)\langle f|H_1|k\rangle\mathrm{e}^{\mathrm{i}(E_f-E_k)t} \;. \tag{C.5}$$

This equation is exact but can only be solved numerically. A perturbative solution for small t is found by using (C.3) to use the first approximation $\gamma_i(t) = 1$:

$$i\hbar\frac{\mathrm{d}\gamma_f(t)}{\mathrm{d}t} \;=\; \langle f|H_1|i\rangle\mathrm{e}^{\mathrm{i}(E_f-E_i)t} \;. \tag{C.6}$$

This equation can be directly integrated to give the first order time-dependent perturbation theory estimate of γ_f:

$$\gamma_f^1(t) = \frac{-2i}{\pi} \mathrm{e}^{\mathrm{i}(E_f - E_i)t/2\hbar} \langle f|H_1|i\rangle \; \Delta_t(E_f - E_i) \; . \tag{C.7}$$

In this expression we have introduced a limiting form of the Dirac distribution

$$\Delta_t(E_f - E_i) = \frac{1}{\pi} \frac{\sin(E_f - E_i)t/2\hbar)}{E_f - E_i} \tag{C.8}$$

which we discuss below.

Squaring this amplitude, we find the probability that the system is in the state f at time t

$$P_{if}(t) = \frac{2\pi t}{\hbar} |\langle f|H_1|i\rangle|^2 \delta_t(E_f - E_i) \; , \tag{C.9}$$

where $\delta_t(E)$, which we will discuss below, is a function that is peaked at $E = 0$ with a width $\Delta E \sim \hbar/t$:

$$\delta_t(E) = \frac{1}{\pi} \frac{\sin^2(Et/2\hbar)}{E^2 t/2\hbar} \; . \tag{C.10}$$

In the limit $t \to \infty$ δ_t approaches the Dirac delta function:

$$\int_{-\infty}^{\infty} \delta_t(E) \mathrm{d}E = 1 \; . \tag{C.11}$$

This means that at large time $[t(E_f - E_i))/\hbar \gg 1]$ the only states that are populated are those that conserve energy to within the Heisenberg condition $\Delta E \, t > \hbar$.

If for some reason the first-order probability vanishes, second-order perturbation theory gives

$$P_{if}(t) = \frac{2\pi t}{\hbar} \left| \sum_{j \neq i,f} \frac{\langle f|H_1|j\rangle \langle j|H_1|i\rangle}{E_j - E_i} \right|^2 \delta_t(E_f - E_i) \; . \tag{C.12}$$

The *transition rate* is found by simply dividing the probability by the time t:

$$\lambda_{if} = \frac{P_{if}(t)}{t} \tag{C.13}$$

Total transition rates are found by summing (C.13) over all final states f.

$$\lambda \;=\; \sum_f \frac{P_{if}(t)}{t} \;=\; \frac{2\pi}{\hbar} \sum_f |\langle f|H_1|i\rangle|^2 \delta_t(E_f - E_i) \; . \tag{C.14}$$

If the states f form a continuum with $\rho_f(E)\mathrm{d}E$ states within the energy interval $\mathrm{d}E$ and if all these states have the same matrix element, we can simply replace the sum by an integral and find the *Fermi golden rule*:

$$\lambda \;=\; \frac{2\pi}{\hbar} |\langle f|H_1|i\rangle|^2 \rho_f(E_i) \; . \tag{C.15}$$

C.0.2 Limiting forms of the delta function

In the above expressions, it has been useful to introduce the functions :

$$\mathit{\Delta}_T(E) = \frac{1}{\pi}\frac{\sin(ET/2\hbar)}{E} \tag{C.16}$$

and

$$\delta_T(E) = \frac{1}{\pi}\frac{\sin^2(ET/2\hbar)}{E^2T/2\hbar} \quad . \tag{C.17}$$

We note that

$$\int_{-\infty}^{\infty} \mathit{\Delta}_T(E) = 1 \quad , \tag{C.18}$$

and

$$\int_{-\infty}^{\infty} \delta_t(E) = 1 \quad . \tag{C.19}$$

In the limit $T \to \infty$, these two functions tend, in the sense of distributions, to the Dirac distribution

$$\lim_{T\to\infty} \mathit{\Delta}_T(E) = \lim_{T\to\infty} \delta_T(E) = \delta(E) \quad . \tag{C.20}$$

They are related by :

$$(\mathit{\Delta}_T(E))^2 = \frac{T}{2\pi\hbar}\delta_T(E) \quad , \quad \forall T \quad . \tag{C.21}$$

The generalization to three variables is straightforward:

$$\mathit{\Delta}_L^3(\boldsymbol{p}) = \prod_{i=1}^{3} \mathit{\Delta}_L(p_i) \quad , \quad \delta_L^3(\boldsymbol{p}) = \prod_{i=1}^{3} \delta_L(p_i) \quad , \tag{C.22}$$

with $\boldsymbol{p} = (p_1, p_2, p_3)$. We have quite obviously

$$\lim_{L\to\infty} \mathit{\Delta}_L^3(\boldsymbol{p}) \;=\; \lim_{L\to\infty} \delta_L^3(\boldsymbol{p}) = \delta^3(\boldsymbol{p})\,, \tag{C.23}$$

and

$$(\mathit{\Delta}_L^3(\boldsymbol{p}))^2 \;=\; \frac{L^3}{(2\pi\hbar)^3}\delta_L^3(\boldsymbol{p}) \quad \forall L\ . \tag{C.24}$$

D. Neutron transport

In this appendix, we give a few more details about neutron transport in matter and the Boltzmann equation used in Sect. 6.7. We refer to the literature[1] for more complete details.

D.0.3 The Boltzmann transport equation

The Boltzmann transport equation governs the behavior of neutrons in matter. We shall write it under the following assumptions:

- The medium is static (neglecting small thermal motions); it is, spherical, homogeneous, and consists of ^{239}Pu nuclei.
- Neutron–neutron scattering is negligible (since the density of neutrons is much smaller than the density of the medium) ;
- Neutron decay is negligible, i.e. the neutron lifetime is very large compared to the typical time differences between two interactions.

The neutrons are described by their density in phase space

$$\frac{\mathrm{d}N}{\mathrm{d}^3\boldsymbol{p}\mathrm{d}^3\boldsymbol{r}} = f(\boldsymbol{r},\boldsymbol{p},t) \quad , \tag{D.1}$$

where $\mathrm{d}N$ is the number of neutrons in the phase space element $\mathrm{d}^3\boldsymbol{p}\mathrm{d}^3\boldsymbol{r}$. The space density of neutrons and the current describing the spatial flow of neutrons are the integrals over the momentum

$$\begin{aligned} n(\boldsymbol{r},t) &= \int f(\boldsymbol{r},\boldsymbol{p},t)\mathrm{d}^3\boldsymbol{p} \,, \\ \boldsymbol{J}(\boldsymbol{r},t) &= \int \boldsymbol{v} f(\boldsymbol{r},\boldsymbol{p},t)\mathrm{d}^3\boldsymbol{p} \,. \end{aligned}$$

In the absence of collisions, neutron momenta are time-independent and the flow of particles in phase space is generated by the motion of particle at velocities $\boldsymbol{v} = \boldsymbol{p}/m$. The density f satisfies an equation of the form

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[1] See for instance, E. M. Lifshitz and L. P. Pitaevskii *Physical Kinetics*, Pergamon Press, 1981; C. Cercignani, *Theory and application of the Boltzmann Equation*, Scottish Academic Press, 1975.

$$\frac{\partial f}{\partial t} + \boldsymbol{v}\cdot\boldsymbol{\nabla} f \ = \ \mathcal{C}(f)\ , \tag{D.2}$$

where $\mathcal{C}(f)$ is the term arising from collision processes, for which we will find an explicit form shortly. For $\mathcal{C}(f) = 0$, (D.2) is called the *Liouville equation.*

The elastic scattering and absorption rates λ_{el} and λ_{abs} are products of the elementary cross-sections, the density of scattering centers n_{239}, and the mean velocity v

$$\lambda_{\mathrm{el}} \ = \ v n_{239}\sigma_{\mathrm{el}} \qquad \lambda_{\mathrm{abs}} \ = \ v n_{239}\sigma_{\mathrm{abs}} \tag{D.3}$$

The absorption is due to both (n,γ) reactions and to fission

$$\sigma_{\mathrm{abs}} \ = \ \sigma_{(\mathrm{n},\gamma)} \ + \ \sigma_{\mathrm{fis}}\ . \tag{D.4}$$

The collision term is then written as

$$\begin{aligned} \mathcal{C}(f(\boldsymbol{p})) \ = \ & n_{239}\int \mathrm{d}^3\boldsymbol{p}' v(p')\, f(\boldsymbol{r},\boldsymbol{p}',t)\frac{\mathrm{d}\sigma}{\mathrm{d}^3\boldsymbol{p}'}(\boldsymbol{p}'\to\boldsymbol{p}) \\ & -[\lambda_{\mathrm{el}}+\lambda_{\mathrm{abs}}]f(\boldsymbol{r},\boldsymbol{p},t) \ + \ S(\boldsymbol{r},\boldsymbol{p})\ . \end{aligned} \tag{D.5}$$

The first term accounts for neutrons coming from the elements of phase space $\mathrm{d}^3\boldsymbol{r}\mathrm{d}^3\boldsymbol{p}'$ which enter the element of phase space $\mathrm{d}^3\boldsymbol{r}\mathrm{d}^3\boldsymbol{p}$ by elastic scattering. The second term represents the neutrons which leave the element $\mathrm{d}^3\boldsymbol{r}\mathrm{d}^3\boldsymbol{p}$ either by elastic scattering or by absorption. The last term $S(\boldsymbol{r},\boldsymbol{p})$ is a source term, representing the production of neutrons by fission.

D.0.4 The Lorentz equation

We recall that we assume the neutrons all have the same time-independent energy, and that the medium is homogeneous.

In that case, the differential elastic scattering cross-section is

$$\frac{\mathrm{d}\sigma}{\mathrm{d}^3\boldsymbol{p}'}(\boldsymbol{p}\to\boldsymbol{p}') \ = \ p^{-2}\delta(p-p')\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\ . \tag{D.6}$$

We also assume, for simplicity, that the scattering cross section is isotropic

$$\frac{\mathrm{d}\sigma_{\mathrm{el}}}{\mathrm{d}\Omega} = \frac{\sigma_{\mathrm{el}}}{4\pi} \quad . \tag{D.7}$$

Later on, we will also make the assumption that all neutrons have the same velocity, v, i.e. that the function $f(\boldsymbol{r},\boldsymbol{p})$ is strongly peaked near values of momentum satisfying $|\boldsymbol{p}| = m_{\mathrm{n}}v$.

Using (D.7) we find that the Boltzmann equation (D.2) and (D.5) reduces to the *Lorentz equation*

$$\frac{\partial f}{\partial t} + \boldsymbol{v}\cdot\boldsymbol{\nabla} f \ = \ \lambda_{\mathrm{el}}(\bar{f}-f) - \lambda_{\mathrm{abs}} f + S(\boldsymbol{r},\boldsymbol{p})\ , \tag{D.8}$$

where

$$\bar{f}(\boldsymbol{r},p,t) = \frac{1}{4\pi}\int f(\boldsymbol{r},\boldsymbol{p},t)\mathrm{d}\Omega_p \quad , \tag{D.9}$$

is the phase-space density averaged over momentum directions.

The Lorentz equation has a large range of applications. It applies to electric conduction, to thermalization of electrons in solids, to the transfer of radiation in stars or in the atmosphere, and to the diffusion of heat, as well as to neutron transport.

It is useful to integrate the Lorentz equation over $\mathrm{d}^3\boldsymbol{p}$, yielding

$$\frac{\partial n}{\partial t} + \boldsymbol{\nabla}\cdot\boldsymbol{J} = -\lambda_{\mathrm{abs}} n + 4\pi S(\boldsymbol{r}) \ , \tag{D.10}$$

where $4\pi S(\boldsymbol{r})$ is the momentum integral of $S(\boldsymbol{p},\boldsymbol{r})$. Furthermore, multiplying the Lorentz equation by $\boldsymbol{v}$ and integrating over $\mathrm{d}^3\boldsymbol{p}$, we obtain :

$$\frac{\partial \boldsymbol{J}}{\partial t} + \int \boldsymbol{v}(\boldsymbol{v}\cdot\boldsymbol{\nabla} f(\boldsymbol{r},\boldsymbol{p},t))\,\mathrm{d}^3\boldsymbol{p} = -(\lambda_{\mathrm{el}}+\lambda_{\mathrm{abs}})\boldsymbol{J} \ , \tag{D.11}$$

where we have assumed that the source term $S(\boldsymbol{p},\boldsymbol{r})$ is independent of the direction of $\boldsymbol{p}$.

Equations (D.10) and (D.11) are the basic equations that we want to solve. The integral

$$I = \int \boldsymbol{v}(\boldsymbol{v}\cdot\boldsymbol{\nabla} f(\boldsymbol{r},\boldsymbol{p},t))\mathrm{d}^3\boldsymbol{p} \ , \tag{D.12}$$

in the left hand side of (D.11) contains all the physical difficulties of the problem. There are two extreme situations.

1. The first is the *ballistic* regime, where the mean free path is much larger than the size of the medium. Collisions have a weak effect and the drift time $\propto 1/(\boldsymbol{v}\cdot\boldsymbol{\nabla} f(\boldsymbol{r},\boldsymbol{p},t))$ controls the evolution. This is the case of electron movement in the base of a transistor.
2. Conversely, in the *diffusive regime* or local quasi-equilibrium regime which is of interest here, the mean free path between two collisions is small compared to the size of the medium. In first approximation, $f(\boldsymbol{r},\boldsymbol{p},t)$ is independent of the direction of $\boldsymbol{p}$ so $f(\boldsymbol{r},\boldsymbol{p}) \sim \bar{f}(\boldsymbol{r},p)$ and we can write this distribution function in the form

   $$f(\boldsymbol{r},\boldsymbol{p},t) = \bar{f}(\boldsymbol{r},p,t) + f_1(\boldsymbol{r},\boldsymbol{p},t) \tag{D.13}$$

   where $f_1 \ll \bar{f}$ contains all the anisotropy, and $\int f_1(\boldsymbol{r},\boldsymbol{p},t)\mathrm{d}^3\boldsymbol{p} = 0$, i.e. f_1 does not contribute to the density n but only to the current $\boldsymbol{J}$.
3. There exist mixed situations, where the medium has large density variations in the vicinity of which none of these approximations holds. This is the case for neutrino transport in the core of supernovae during the rebound of nuclear matter. Such situations require sophisticated numerical techniques.[2]

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[2] See for instance J-L. Basdevant, Ph.Mellor and J.-P. Chièze, "Neutrinos in Supernovae, An exact treatment of transport," Astronomy and Astrophysics, vol.197, p 123 (1988)

We place ourselves in the case (D.13). (This assumption amounts to expanding the distribution function in Legendre polynomials, or spherical harmonics, and in retaining only the first two terms of the expansion.) We neglect the anisotropic part f_1 in the integral (D.12). Since $\bar{f}$ is independent of the direction of $\boldsymbol{p}$, the integral over angles is simple

$$I \;=\; \frac{v^2}{3}\boldsymbol{\nabla} n(\boldsymbol{r},t) \tag{D.14}$$

and (D.11) becomes

$$\frac{\partial \boldsymbol{J}}{\partial t} + \frac{v^2}{3}\boldsymbol{\nabla} n \;=\; -(\lambda_{\mathrm{el}} + \lambda_{\mathrm{abs}})\boldsymbol{J}\ . \tag{D.15}$$

Equations (D.10) and (D.15) are now the basic equations to be solved.

Pure Diffusion. We first consider a situation where there is no absorption and no source term, i.e. the case of pure diffusion where where there is only elastic scattering with the nuclei of the medium. The two equations (D.10) and D.15) reduce to

$$\frac{\partial n}{\partial t} + \boldsymbol{\nabla}\boldsymbol{J} \;=\; 0\ , \tag{D.16}$$

$$\frac{\partial \boldsymbol{J}}{\partial t} + \frac{v^2}{3}\boldsymbol{\nabla} n \;=\; -\lambda_{\mathrm{el}}\boldsymbol{J}\ . \tag{D.17}$$

The first relation expresses the conservation of the number of particles (one can write energy conservation in the same manner). The second expresses the current density in terms of the gradient of the density of particles

$$\boldsymbol{J} \;=\; -D\left[v\boldsymbol{\nabla} n + \frac{3}{v}\frac{\partial \boldsymbol{J}}{\partial t}\right]\ , \tag{D.18}$$

where the *diffusion coefficient* D depends on the velocity and the elastic-scattering rate

$$D \;=\; \frac{v}{3\lambda_{\mathrm{el}}} \;=\; \frac{l}{3}\ , \tag{D.19}$$

where in the second form we use the fact that $\sigma_{\mathrm{tot}} = \sigma_{\mathrm{el}}$ implying that the mean free path is $l = v/\lambda_{\mathrm{el}}$. Under the conditions (which occur frequently) where $(3/v)\partial\boldsymbol{J}/\partial t$ can be neglected, this boils down to Fick's law, where the current is proportional to the density gradient:

$$\boldsymbol{J} \;=\; -Dv\boldsymbol{\nabla} n\ . \tag{D.20}$$

Inserting (D.18) into (D.16) leads to

$$\frac{\partial n}{\partial t} + \frac{3D}{v}\frac{\partial^2 n}{\partial t^2} - Dv\nabla^2 n \;=\; 0\ , \tag{D.21}$$

which is called the *telegraphy equation* .

This equation has the general form of a wave equation where the wavefront propagates with the velocity $v/\sqrt{3}$ but the wave decreases exponentially with the distance. If the mean free path $1/3D$ is small compared to the dimension R of the system under consideration, the propagation time $\tau = v/R\sqrt{3}$ of the wave in the system is very short compared to the time of migration of a neutron by a random walk on the same distance. One can therefore neglect the propagation term $(3D/v)\partial^2 n/\partial t^2$ which amounts to considering the propagation velocity as infinite in the telegraphy equation.[3]

In this approximation, one ends up with the *Fourier diffusion equation*

$$\frac{\partial n}{\partial t} = Dv\nabla^2 n \;, \tag{D.22}$$

which has a large range of applications and which can be solved by taking the Fourier transformation. We set

$$n(\boldsymbol{r},t) = \int e^{i\boldsymbol{k}\cdot\boldsymbol{r}} g(\boldsymbol{k},t)\mathrm{d}^3\boldsymbol{k} \;, \tag{D.23}$$

and, by inserting this into (D.22), we obtain

$$\frac{\partial g}{\partial t} = -k^2 Dvg \;, \tag{D.24}$$

i.e.

$$g(\boldsymbol{k},t) = f(\boldsymbol{k})e^{-k^2 Dvt} \;, \tag{D.25}$$

where $f(\boldsymbol{k})$ is determined by the initial conditions using the inverse Fourier transform

$$n(\boldsymbol{r},t = 0) = \int e^{i\boldsymbol{k}\boldsymbol{r}} f(\boldsymbol{k})\mathrm{d}^3\boldsymbol{k} \quad , \tag{D.26}$$

i.e.

$$f(\boldsymbol{k}) = (2\pi)^3 \int e^{-i\boldsymbol{k}\cdot\boldsymbol{r}} n(\boldsymbol{r},t=0)\mathrm{d}^3\boldsymbol{r} \;. \tag{D.27}$$

If at time $t = 0$ the density n is concentrated at the origin, $n(\boldsymbol{r},t = 0) = n_0\delta(\boldsymbol{r})$, $f(\boldsymbol{k})$ is then a constant f, and $n(\boldsymbol{r},t)$ is the Fourier transform of a Gaussian:

$$n(\boldsymbol{r},t) \propto e^{-r^2/4Dvt} \;. \tag{D.28}$$

The diffusion time T in a sphere of radius R is of the order of $T \sim (R^2/Dv) = (R/\lambda)^2(\lambda/v)$ where λ/v is the mean time between two elementary collisions.

The telegraphy equation (D.21) can also be treated by Fourier transform. One can directly check under which conditions the propagation term $(3D/v)\partial^2 n/\partial t^2$ can be neglected.

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[3] We remark that the Fourier equation is a bona fide wave equation with exponential damping at infinity. The wavefronts have a finite velocity $v/\sqrt{3}$, however the propagation effects are completely negligible in the diffusion regime.

E. Solutions and Hints for Selected Exercises

Chapter 1

1.9 One has

$$\langle E\rangle = A\langle\frac{p^2}{2m}\rangle - \frac{A(A-1)}{2}g^2\langle\frac{1}{r}\rangle \quad .$$

Therefore, owing to the Heisenberg + Pauli inequality $\langle p^2\rangle \geq A^{2/3}\hbar^2(\langle 1/r\rangle)^2$ we obtain

$$\langle E\rangle \geq A^{5/3}\hbar^2\frac{1}{2m}\langle\frac{1}{r}\rangle^2 - \frac{A(A-1)}{2}g^2\langle\frac{1}{r}\rangle \quad .$$

Minimizing with respect to $\langle 1/r\rangle$, we obtain

$$\langle E\rangle/A \sim -mg^4A^{4/3}/8\hbar^2 \qquad \text{and}\langle 1/r\rangle \sim 2\hbar^2A^{-1/3}/mg^2 \quad .$$

1.12 The ratio of the quadrupole and magnetic hyperfine splittings for a very elongated nucleus is of order

$$\frac{Z^2R^2/a_0^2}{\alpha^2m_\mathrm{e}/m_\mathrm{p}} \sim 0.3\,Z^2$$

where we use $R \sim 5\,\mathrm{fm}$ and $a_0 = \hbar c/\alpha m_\mathrm{e}c^2$. For a slightly deformed nucleus, R^2 is replaced by $Q \propto R^2\Delta R/R$ (Q is the mass quadrupole moment). This lowers the quadrupole splitting by a factor of more then 10. The sign of this splitting is opposite for prolate and oblate nuclei whereas the magnetic splitting is shape independent.

1.13 The energy splitting is $\Delta E = 2 \times 2.79\mu_N = 1.76 \times 10^{-7}\mathrm{eV}$. For $kT = 0.025\,\mathrm{eV}$ this gives a difference in population of

$$\frac{\mathrm{e}^{\Delta E/2kT} - \mathrm{e}^{-\Delta E/2kT}}{\mathrm{e}^{\Delta E/2kT} + \mathrm{e}^{-\Delta E/2kT}} \sim \Delta E/2kT \sim 3.5 \times 10^{-6}\ .$$

The absorption frequency is $\Delta E/2\pi\hbar = 4.2 \times 10^7\,\mathrm{Hz}$.

Medical applications of MRI are confined to hydrogen since ^{1}H is the only common nuclide with spin.

The magnetic field due to neighboring spins is of order $(\mu_0/4\pi)\mu_N/a_0^3 \sim 5 \times 10^{-3}\mathrm{T}$.

1.16 The data indicates that the value of m/Z for ^{48}Mn is about midway between the values for ^{46}Cr and ^{50}Fe. Using a ruler, one can find that $m/Z(\mathrm{Mn}) \sim \mathrm{f} \times \mathrm{m/Z(Fe)} + (1-\mathrm{f}) \times \mathrm{m/Z(Cr)}$ with $f \sim 0.54 \pm 0.01$. The values of B/A for ^{46}Cr and ^{50}Fe imply $m/Z(\mathrm{Cr}) = 1783.624\,\mathrm{MeV}$ and $m/Z(\mathrm{Fe}) = 1789.497$ so $m/Z(\mathrm{Mn}) = 1786.74 \pm 0.06$. This gives $B/A(^{48}\mathrm{Mn}) = (8.26 \pm 0.03)\,\mathrm{MeV}$. The experimenters (not obliged to use a ruler) give an uncertainty of 0.002 MeV.

1.17 The protons initially have kinetic energy $E_\mathrm{p} = 11\,\mathrm{MeV}$ corresponding to a momentum $p_\mathrm{p}c = \sqrt{2E_\mathrm{p}m_\mathrm{p}c^2} = 143\,\mathrm{MeV}$. For protons recoiling from Ni nuclei in the 1.35 MeV excited state, to first approximation, the proton energy is reduced by this amount, i.e. $E'_\mathrm{p} = 11 - 1.35 = 9.65\,\mathrm{MeV}$. This corresponds to a proton momentum $p'_\mathrm{p}c = 134\,\mathrm{MeV}$. Momentum conservation then allows us to deduce the momentum components of the recoiling ^{64}Ni nucleus if the proton scatters at an angle θ:

$$p_t c \;=\; (134 \sin\theta)\,\mathrm{MeV} \qquad\qquad p_l c \;=\; (143 - 134\cos\theta)\,\mathrm{MeV}\ ,$$

for the directions perpendicular to and along the beam direction. For $\theta = 60$ deg, this gives a Ni momentum of $pc = 139\,\mathrm{MeV}$ and a kinetic energy of 0.16 MeV. We can then re-estimate the energy of protons recoiling at 60 deg to be $9.65 - 0.16 = 9.49\,\mathrm{MeV}$.

Chapter 2

2.4 The simplest way to demonstrate the equivalence is to write down the 3-d wavefunctions in terms of products of 1-d harmonic oscillatory wavefunctions and show that they are proportional to the appropriate spherical harmonics: $Y_{10} \propto \cos\theta$ and $Y_{1\,\pm1} \propto \sin\theta \mathrm{e}^{\pm\mathrm{i}\phi}$.

2.6 ^{41}Ca has one neutron outside closed shells containing 20 protons and 20 neutrons. The orbital above 20 particles is 1f7/2 so $J = 7/2$ and $l = 3$ implying that the parity is negative (-1^l). So spin$^{\mathrm{parity}} = 7/2^-$ in agreement with observation.

2.7 ^{83}Kr has an odd neutron orbiting closed shells while ^{93}Nb has an odd proton. The odd proton contributes to the magnetic moment through both its spin and orbital angular momentum while the neutron contributes only its spin. For $J = 9/2$, the orbital moment must dominate so we expect ^{93}Nb to have the greater moment. For ^{93}Nb, the Schmidt formulas give (for $l = 4$ or $l = 5$):

$$g \;=\; (9/2 - 1/2) \;+\; 2.79 \;=\; 6.79 \qquad \text{or} \qquad (9/11)[6 - 2.79] \;=\; 2.62\ .$$

The shell model suggests $l = 4 \Rightarrow g = 6.79$ to be compared with the experimental value 6.167.

For ^{86}Kr the Schmidt formulas give:

$$g \;=\; -1.91 \qquad \text{or} \qquad (9/11)1.91 \;=\; 1.56\ .$$

The shell model suggests $l = 4 \Rightarrow g = -1.91$ to be compared with the experimental value -0.97.

In both cases, the experimental values are between the two Schmidt values and somewhat closer to the value predicted by the shell model.

Chapter 3

3.2 The neutrino flux (integrated over the duration of the pulse $\sim 15\ s$) was $F = N/(4\pi R^2) = 10^{57}/(3\ 10^{43})$, the number of protons in the target was $N_c = (4/3)10^{32}$. The number of events detected is $F\ N_c\ \sigma \simeq 10$. One can meditate on the many elements of the observers good luck. (The Kamiokande detector had been built 2 years before to observe a completely different phenomenon, the as yet unobserved proton decay).

3.6 To first approximation, the scattered electron keeps all of its energy so its momentum components perpendicular and parallel to the beam directions are $p_t c \sim 500\,\mathrm{MeV} \times \sin\theta$ and $p_l c \sim 500\,\mathrm{MeV} \times \cos\theta$. Momentum conservation then gives the momentum of the recoiling target particle

$$p_t c \sim 500\,\mathrm{MeV} \times \sin\theta \qquad p_l c \sim 500\,\mathrm{MeV} \times (1 - \cos\theta)\ .$$

For $\theta = 45$ deg this gives a recoil energy of 78 MeV for a nucleon and 39 MeV for a deuteron. Subtracting this from the electron energy gives a peak at 422 MeV for recoil from a proton and 461 MeV for recoil from a deuteron. The proton peak energy should be further reduced by the 2.2 MeV necessary to break the deuteron.

3.7 The Rutherford cross-section is

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{\alpha^2(\hbar c)^2}{16E^2 sin^4(\theta/4)}\ .$$

Equating this with the strong-interaction cross-section, $\sim (10\,\mathrm{fm})^2\,\mathrm{sr}^{-1}$, gives $\sin\theta/2 \sim 0.13$, i.e. $\theta \sim 16$ deg. At smaller angles Rutherford scattering dominates while at higher angles strong-interaction scattering dominates. It should be kept in mind that the *amplitudes* for the two interactions must be summed. This permits one to determine their relative phases.

Chapter 4

4.4 The maximum energy photons have about 15 keV excess energy out of 1065 keV so the decaying nuclei initially have $v/c \sim 1.4 \times 10^{-2}$ corresponding to an energy $\sim 7\,\mathrm{MeV}$. The Bethe–Bloch formula gives an energy loss of $\sim 2 \times 10^6\,\mathrm{MeV}(\mathrm{g\,cm}^{-2})^{-1}$ or about $2 \times 10^7\,\mathrm{MeV\,cm}^{-1}$ in nickel. The Br ions then would stop after $\sim 3 \times 10^{-7}\,\mathrm{cm}$ in a time of about $10^{-15}\,\mathrm{s}$. Since it appears that about half the nuclei decay before stopping, this would mean that the lifetime is of order 10^{-15}s. In fact, because at very low velocities the ion attaches electrons reducing its effective charge, the Bethe–Bloch formula overestimates by about a factor ~ 100 the energy loss for Br ions at $v/c \sim 10^{-2}$ (see L.C. Northcliffe and R.F. Schilling Nuclear Data Tables, **A7** (1970) 233; F.S. Goulding and B.G. Harvey, Ann. Rev. Nucl. Sci **25** (1975) 167.). The stopping time is thus a factor of ~ 100 greater and the lifetime is $\sim 0.5 \times 10^{-12}$s.

4.5 The decay of ^{60}Co to the ground and first excited states of ^{60}Ni are forbidden ($\Delta J > 1$) so the decay is primarily by the allowed transition to the 4^+ state. The 4^+ state decay to the ground state is M4 so the decay is primarily through the cascade of two E2 transitions. For $E_\gamma \sim 1\,\mathrm{MeV}$ such transitions have mean lives of $\sim 10^{-12}$ s.

4.9 ^{152m}Eu has an allowed Gamow-Teller decay to the 1^- state of ^{152}Sm while the decays of the ^{152}Eu to the shown states are forbidden.

The kinetic energy of the recoiling Sm is $p^2c^2/2mc^2 = (840\,\mathrm{keV})^2/(2 \times 145\,\mathrm{GeV}) = 2.4\,\mathrm{eV}$ corresponding to a velocity of $v/c \sim 6 \times 10^{-6}$. The 961 keV photons emitted in the direction of the Sm velocity are thus blue shifted to an energy of $961(1 + 6 \times 10^{-6})$ keV. This gives them enough energy to excite a second Sm nuclei (taking into account the recoil of the second Sm).

4.10 To good approximation the neutrino conserves its energy $\sim 5\,\mathrm{MeV}$ so a neutron recoiling from a back-scattered neutrinos has an energy $p^2c^2/2m_\mathrm{n}c^2 \sim (5\,\mathrm{MeV})^2/2\,\mathrm{GeV} \sim 12\,\mathrm{keV}$. The cross-section for such neutrons on hydrogen nuclei is ~ 20 b corresponding to a mean free path of ~ 1 cm in CH. This neglects the carbon, which has a smaller cross-section, ~ 5 b. Since a neutron loses on average half its kinetic energy in a collision with a proton (isotropic scattering at low energy), about 17 collisions are necessary to reduce the energy by five orders of magnitude to a reasonably thermal energy, 0.1 eV.

The absorption cross-section is about 0.1 b for thermal neutrons and they have $v \sim 4 \times 10^5\mathrm{cm\,s^{-1}}$. This gives a mean absorption time of

$$\left[10^{-25}\mathrm{cm}^2 \times 4 \times 10^5\mathrm{cm\,s^{-1}} \times 6 \times 10^{23}/13\right]^{-1} \sim 0.5\,\mathrm{ms}\ .$$

Chapter 5

5.4

$$t \sim 8200\,\mathrm{yr} \times \ln\left(\frac{0.233}{19.6 \times 10^{-4}}\right) \sim 3.9 \times 10^4\,\mathrm{yr}\ .$$

5.5 Assuming equal initial amounts of ^{235}U and ^{238}U, the elapsed time since creation is

$$\frac{7 \times 10^8\,\mathrm{yr}/\ln 2}{1 - 0.7/4.5} \ln\left(\frac{99.27}{0.72}\right) \sim 5.9 \times 10^9\,\mathrm{yr}\ .$$

Assuming the same for ^{234}U and ^{238}U, one finds 3.5×10^6 yr. The discrepancy is due to the fact that most of the original ^{234}U has decayed so the ^{234}U now present comes from the decay chain initiated by ^{238}U. In this case, one expects $^{234}\mathrm{U}/^{238}\mathrm{U} = \mathrm{t}_{1/2}(234)/\mathrm{t}_{1/2}(238)$ in agreement with the measured values.

5.6 The α-particle originally has $\beta^2 \sim 2 \times 10^{-3}$ so the initial energy loss is $\sim 1000\,\mathrm{MeV\,cm^{-1}}$ for $\rho = 1.8\,\mathrm{g\,cm^{-3}}$. The probability that it produces a neutron before losing 1 MeV is

$$\begin{aligned} P &= (1/1000)\,\mathrm{cm} \times 0.4 \times 10^{-24}\,\mathrm{cm}^2 \times 1.8\,\mathrm{g\,cm^{-3}} \\ &\qquad \times (6 \times 10^{23}/9)\,\mathrm{g}^{-1} \sim 5 \times 10^{-5}\,, \end{aligned}$$

so to give 1 Bq neutron activity we need 2×10^4 Bq of α activity.

Chapter 6

6.3 The mean free path for neutrons is dominated by fission of ^{235}U:

$$l^{-1} = 250 \times 10^{-24}\mathrm{cm}^2 \times \frac{6 \times 10^{23}}{238} \times 0.0072 \times 19\,\mathrm{g\,cm^{-3}} \sim 11\,\mathrm{cm}\,.$$

If the uranium is in the shape of a cube, the probability of a fission is $P = 1\,\mathrm{cm}/11\,\mathrm{cm}$ and the fission rate is

$$(1/11) \times 10^{12}\,\mathrm{cm^{-2}s^{-1}} \sim 10^{12}\,\mathrm{s^{-1}}$$

corresponding to ~ 30 W. The rate is lower if the uranium is deformed so that the dimension in the direction of the beam is comparable to or greater than the mean free path.

6.5 Neutron-rich fission products with $A = 142$ will β^--decay to ^{142} Ce which is a long-live 2β emitter.

6.6 The nuclides with $A \sim 100$ are fission products. The transuraniums ^{243}Am and ^{239}Pu are produced by neutron captures (followed by β-decays) on ^{238}U. The nuclides with $210 < A < 235$ come from the decay chains initiated by the transuraniums.

Chapter 7

7.4 The photon energy is 17.49 MeV (as above). Using the Bethe–Bloch formula, the energy loss of the proton in the LiF is

$$\Delta E \sim 10^{-5}\mathrm{g\,cm^{-2}} \times \frac{1\,\mathrm{MeV}\,(\mathrm{g\,cm^{-2}})^{-1}}{\beta^2} \sim 20\,\mathrm{keV}$$

where we use $\beta^2 = 4 \times 10^{-4}$ for the proton. The actual energy loss is ~ 5 times less since the Bethe–Bloch formula overestimates the energy loss at this velocity.

The cross-section is proportional to $\propto \exp(-\sqrt{E_B/E})$ where $E_B \sim 7.75$ MeV for this reaction. This gives the variation of the cross-section as the incident proton loses energy in the LiF:

$$\frac{\mathrm{d}\sigma}{\sigma} = (1/2)\sqrt{E_B/E}\frac{\Delta E}{E} \sim 3\,\frac{\Delta E}{E} \sim 0.05\,,$$

so the cross-section is relatively constant over the thickness of the target. If the target were much thicker, the variation would be substantial and the event rate would not be easily interpretable.

7.5 The parameters entering the calculations are $E_B = 7.75\,\mathrm{MeV}$, $E_\mathrm{G} = 12.45\,\mathrm{keV}$, $\Delta E_\mathrm{G} = 0.3\,\mathrm{keV}$, $S(E_\mathrm{G}) = -.5\,\mathrm{keV\,b}$, and $\Gamma_\gamma = 12\,\mathrm{eV}$. The factor that deviates most from unity is the Boltzmann factor giving the probability to have a proton with enough energy to excite the resonance: $\exp(-441\,\mathrm{keV}/kT)$. This makes the resonance contribution completely negligible at $kT = 1\,\mathrm{keV}$.

7.6 For $T = 10^6\,\mathrm{K}$, $kT = 0.086\,\mathrm{keV}$ we have $nkT\tau_\mathrm{brem} \sim 3 \times 10^{19}\,\mathrm{keV\,m^{-3}\,s}$ in agreement with the figure. It is proportional to $T^{3/2}$, also in agreement with the figure.

Chapter 8

8.4 The mean free path of a 10 MeV neutrino in a neutron star is of order

$$l = \left[\frac{10^{57}}{(4\pi/3)(10^4\,\mathrm{m})^3} 10^{-41}\,\mathrm{cm}^2\right]^{-1} \sim 4\,\mathrm{m}\,,$$

which is much less than the neutron star radius, $R \sim 10^4\,\mathrm{m}$. The neutrinos therefore diffuse out of the star with a time of order $R^2/cl \sim 0.1\,\mathrm{s}$. In fact, the neutrino pulse from the collapse of stellar core to a neutron star lasts somewhat longer, about 10 s.

8.7 All degenerate gases have a phase space density of order $\hbar^{-3}$. The phase space density of such a gas is the momentum space density ($\sim p_\mathrm{F}^{-3}$) times the real space density (n) so the Fermi momentum is $p_\mathrm{F}^2 \sim n^{2/3}\hbar^2$. For $p_\mathrm{F} \ll mc$ and $p_\mathrm{F} \gg mc$ this gives a total energy for N fermions

$$E \sim \frac{Np_\mathrm{F}^2}{2m} \sim \frac{Nn^{2/3}\hbar^2}{m} \qquad\qquad E \sim Np_\mathrm{F}c \sim Nn^{1/3}\hbar c\,.$$

The pressure is the derivative of the energy with respect to the volume. We find for the two limits

$$P \sim n^{5/3}\frac{(\hbar c)^2}{mc^2} \qquad\qquad P \sim n^{4/3}\hbar c \quad ,$$

where n is the number density. (The numerical factor in the first case is $(3\pi^2)^{2/3}/5$).

For a number density of electrons $n \sim 10^{30}\ \mathrm{cm}^{-3}$, and a temperature $T \sim 10^7$ K the degenerate quantum pressure $\propto n^{5/3}$ is much larger than a classical ideal gas pressure $\propto n$. Between the density where the star can be treated as an ideal gas and that where it becomes a Fermi gas, there is a transition regime. Above a critical density, and for temperatures smaller than the Fermi temperature, the electron gas becomes degenerate. Notice that owing to the mass effect, the gas of nuclei is still an ideal gas.

For a non-relativistic degenerate electron gas, the strong quantum pressure is temperature independent and it resists futher collapse, since the gravitational inward pressure behaves as $n^{4/3}$. There is no further contraction, no further nuclear reactions, the star cools endlessly. This situation corresponds to a white dwarf.

The order of magnitude of the temperature at which the contracting gas reaches this regime can be estimated from the virial theorem, $\langle 3PV \rangle \sim GM^2/R$. We approximate the pressure by the sum of the classical and quantum pressures. This gives

$$NkT \sim \frac{GM^2}{R} - \frac{N^{5/3}\hbar^2/m}{R^2} \; . \tag{E.1}$$

Minimizing with respect to R we get

$$R \sim \frac{N^{5/3}\hbar^2}{GM^2} \qquad kT_{\max} = \frac{G^2M^2m}{4N^{5/3}\hbar^2} \; ,$$

where M is the mass of the star and m and N are the mass and number of the degenerate particle.

If $T_{max} \leq 10^6$ K, the star is called a brown dwarf because the temperature has not reached the value where nuclear reactions can take place. The difference between a brown dwarf and a planet is that, in a planet, the individual atoms and molecules have not been completely dissociated in a plasma of electrons and nuclei, at least in the crust. The temperature is much lower, the overall cumulative gravitational forces give the object a global spherical shape, but rocks and other non-spherical objects, whose shapes are due to electromagnetic forces, can still exists on the surface.

8.8 The mass of the iron core of a star can increase only up to the Chandrasekhar mass at which point it will collapse. During the collapse, the Fermi energy of the electrons increases until most electrons have sufficient energy to by captured endothermically. The neutrinos produced in the captures do not induce the reverse reaction because they escape from the star after a period of diffusion (Exercise 8.4).

The energy radiated by a neutrino species of temperature T is given by Stefan's law (after a minor modification taking into account the fact that neutrinos are fermions). Taking $kT = 1\,\mathrm{MeV}$, a neutrinosphere radius of $R = 10^4\,\mathrm{m}$, and a pulse duration of $10\,\mathrm{s}$, one finds that the total energy radiated by three neutrino species is

$$5.67 \times 10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}} \times 10\,\mathrm{s} \times (kT)^4\, 4\pi R^2 \sim 3 \times 10^{46}\,\mathrm{J} \; .$$

This agrees with the total energy liberated, $(3/5)GM^2/R$. (The agreement is not fortuitous since the temperature and radius of the neutrino sphere are constrained by this requirement.) Note that the number of neutrinos radiated, $(3 \times 10^{46}\,\mathrm{J})/2kT \sim 2 \times 10^{58}$, is greater than the number of ν_e produced by neutron capture $\sim 10^{57}$. Most of the neutrinos are thermally produced, $\gamma\gamma \leftrightarrow e^+e^- \leftrightarrow \nu\bar{\nu}$.

Chapter 9

9.3 The density of protons when $kT = 60\,\mathrm{keV}$ can be scaled up from the present density by the third power of the temperature:

$$n_{\mathrm{p}} \sim n_{\mathrm{p}}(t_0)(60\,\mathrm{keV}/kT(t_0))^3 = \eta n_\gamma(t_0) \times \left(\frac{60\,\mathrm{keV}}{2 \times 10^{-4}\,\mathrm{eV}}\right)^3 .$$

The reaction rate per neutron is this density multiplied by σv which gives $\sim 3 \times 10^{-3}\mathrm{s}^{-1}$ for $\eta \sim 4 \times 10^{-12}$. This nearly the expansion rate $\sim 0.65\mathrm{s}^{-1}(60\mathrm{keV}/1\,\mathrm{MeV})^2 \sim 2 \times 10^{-3}\mathrm{s}^{-1}$.

The deuteron-neutron ratio at this temperature is

$$\frac{n_2}{n_{\mathrm{n}}} = \eta n_\gamma \left(m_{\mathrm{p}}c^2kT)\right)^{-3/2}(2\pi\hbar c)^3\mathrm{e}^{-B/kT} \sim \eta \times 10^{-18} ,$$

and rises very quickly above unity as the temperature falls.

9.5 We use

$$\dot{a}/a \sim \dot{T}/T \sim 0.65(kT/1\,\mathrm{MeV})^2\,\mathrm{s}^{-1} .$$

Integrating, we get

$$\Delta t \sim \int_{kT\sim 1\,\mathrm{MeV}}^{kT=60\,\mathrm{keV}} \frac{dT}{\dot{T}} \sim 166\,\mathrm{s} .$$

9.7 The wimps have kinetic energies of order $(1/2)mc^2\beta^2 \sim 50\,\mathrm{keV}$. For most nuclear targets, this is much less than the excitation energy of the first excited state so we expect only elastic scattering to be possible.

The mean free path in the Earth is of order

$$l^{-1} \sim 10^{-35}\,\mathrm{cm}^2\,\mathrm{nucleus}^{-1}$$
$$\times(6 \times 10^{23}\mathrm{nucleon}\,\mathrm{g}^{-1}/50\,\mathrm{nucleon/nucleus})\,5\,\mathrm{g\,cm}^{-3} \sim \frac{1}{10^7\,\mathrm{km}} ,$$

i.e, much greater than the radius of the Earth. The interaction rate in one kg of germanium is

$$\lambda \sim \frac{0.3\,\mathrm{GeV\,cm}^{-3}}{50\,\mathrm{GeV/wimp}} \times 3 \times 10^7\mathrm{cm\,s}^{-1} \times 10^{-35}\mathrm{cm}^2$$
$$\times\frac{6 \times 10^{26}\mathrm{nucleon\,kg}^{-1}}{72\mathrm{nucleon/nucleus}} \sim 10^{-5}\mathrm{s}^{-1} ,$$

which is less than the rate of ^{68}Ge decay.

F. Tables of numerical values

Table F.1. Selected physical and astronomical constants, adapted from [1].

quantity	symbol	value
speed of light in vacuum	c	$2.99\,792\,458 \times 10^{8}\ \mathrm{m\,s^{-1}}$
Planck constant	$\hbar$	$1.054\,571\,596(82) \times 10^{-34}\,\mathrm{J\,s}$
conversion constant	$\hbar c$	$197.326\,960\,2(77)\,\mathrm{MeV\,fm}$
conversion constant	$(\hbar c)^2$	$389\,379\,292\,(30)\,\mathrm{MeV^2\,b}$ $(1\,\mathrm{b} \equiv 10^{-28}\,\mathrm{m^2})$
e^- charge magnitude	e	$1.602\,176\,462(63) \times 10^{19}\,\mathrm{C}$ $\Rightarrow 1\,\mathrm{eV} = 1.602 \times 10^{-19}\,\mathrm{J}$
Fine structure constant	$\alpha = e^2/4\pi\epsilon_0\hbar c$	$[137.035\,999\,76(50)]^{-1}$
Bohr radius	a_∞	$0.529\,177\,208\,3(39) \times 10^{-10}\,\mathrm{m}$
Rydberg energy	$\alpha^2 m_\mathrm{e} c^2/2$	$13.605\,691\,72(53)\,\mathrm{eV}$
Thomson cross-section	σ_T	$0.665\,245\,854(15) \times 10^{-28}\,\mathrm{m^2}$
Gravitational constant	$G_\mathrm{N}\ (= G)$	$6.673(10) \times 10^{-11}\,\mathrm{m^3 kg^{-1} s^{-2}}$
Planck mass	$m_\mathrm{pl} = \sqrt{\hbar c/G}$	$1.221\,0(9) \times 10^{19}\,\mathrm{GeV}/c^2$
Fermi coupling constant	$G_\mathrm{F}/(\hbar c)^3$	$1.166\,39(1) \times 10^{-5}\mathrm{GeV^{-2}}$
electron mass	m_e	$0.510\,998\,902(21)\,\mathrm{MeV}/c^2$
proton mass	m_p	$938.271\,998(38)\,\mathrm{MeV}/c^2$ $1.672\,621\,58(13)\,\mathrm{kg}$ $1836.152\,667\,5(39) m_\mathrm{e}$
neutron–proton Δm	$m_\mathrm{n} - m_\mathrm{p}$	$1.293\,318(9)\,\mathrm{MeV}/c^2$
Avogadro constant	N_A	$6.022\,141\,99(47) \times 10^{23}\,\mathrm{mol^{-1}}$
nuclear magneton	$\mu_N = e\hbar/2m_\mathrm{p}$	$3.152\,451\,238(24)\,10^{-14}\mathrm{MeV T^{-1}}$
Boltzmann constant	k	$1.380\,650\,3(24) \times 10^{-23}\mathrm{J\,K^{-1}}$ $8.617\,342(15) \times 10^{-5}\,\mathrm{eV\,K^{-1}}$
parsec	pc	$3.085\,677\,580\,7(4) \times 10^{16}\,\mathrm{m}$ $=3.262...\ \mathrm{ly}$
solar mass	$M_\odot$	$1.988\,9(30) \times 10^{30}\,\mathrm{kg}$ $= 1.189 \times 10^{57} m_\mathrm{p}$
solar luminosity	$L_\odot$	$3.846(8) \times 10^{26}\,\mathrm{W\,s^{-1}}$
solar equatorial radius	$R_\odot$	$6.961 \times 10^{8}\ \mathrm{m}$

G. Table of Nuclei

The following table lists known nuclei sorted by their mass number A. Binding energies are taken from [2] while decay modes, lifetimes (in seconds), and terrestrial abundances (for long-lived isotopes) are generally taken from [3]. For a given A, the binding energies shown in column 2 are the parabolic functions of Z illustrated in Fig. 2.6. Because of the nucleon-pairing energy, their is only one parabola for odd-A and two parabolas for even-A (one for even-even and one for odd-odd). Nuclei on the neutron-rich side of the parabola are generally β^--unstable while those on the proton-rich side are unstable to electron-capture ($Q_{\mathrm{ec}} < 2m_{\mathrm{e}}$) or to both electron-capture and β^+ decay ($Q_{\mathrm{ec}} > 2m_{\mathrm{e}}$). A few very weakly bound nuclei can also decay by nucleon emission, e.g. $A = 16$, $Z = 5, 9, 10$.

Because of the single or double parabolic structure, there is only one β-stable nucleus for odd-A and two or three β-stable nuclei for even-A. For even-A, only one nucleus is also stable against double-β decay, but the lifetime for 2β decay is generally greater than 10^{20} yr so nuclei that are only 2β unstable are still present on Earth.

Nuclei with $A > 150$ ($A > 100$) are also usually unstable to α-decay (spontaneous fission). The lifetimes are generally greater than 10^{20} yr for $A < 208$.

Decay and reaction Q's can be calculated from the binding energies in this table. For example

$$\begin{aligned}
Q_{\beta-}[(A,Z) \to (A,Z+1)] &= B(Z+1) - B(Z) + (m_{\mathrm{n}} - m_{\mathrm{p}} - m_{\mathrm{e}})c^2 \\
&= B(Z+1) - B(Z) + 0.782\,\mathrm{MeV}\ , \\
Q_{\beta+}[(A,Z) \to (A,Z-1)] &= B(Z-1) - B(Z) - (m_{\mathrm{n}} + m_{\mathrm{e}} - m_{\mathrm{p}})c^2 \\
&= B(Z-1) - B(Z) - 1.804\,\mathrm{MeV}\ , \\
Q_{\alpha}[(A,Z) \to (A-4,Z-2)] &= B(A-4,Z-2) - B(A,Z) + B(4,2)\ , \\
&= B(A-4,Z-2) - B(A,Z) + 28.295\ .
\end{aligned}$$

A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %
1 n 0	0.0000	β^-	2.79
1 H 1	0.0000		99.99%
2 H 1	1.1123		0.01%
3 H 1	2.8273	β^-	8.59
3 He 2	2.5727		0.00%
4 H 1	1.3753	n	
4 He 2	7.0739		100.00%
4 Li 3	1.1545	p	
5 H 1	0.2164	n	
5 He 2	5.4811	n	-20.96
5 Li 3	5.2661	p	-21.36
6 H 1	0.9636	n	
6 He 2	4.8782	β^-	-0.09
6 Li 3	5.3324		7.50%
6 Be 4	4.4873	p	-20.15
7 He 2	4.1178	n	-20.39
7 Li 3	5.6064		92.50%
7 Be 4	5.3715	EC	6.66
7 B 5	3.5314	p	-21.33
8 He 2	3.9260	β^-	-0.92
8 Li 3	5.1598	β^-	-0.08
8 Be 4	7.0624	α	-16.01
8 B 5	4.7172	β^+	-0.11
8 C 6	3.0978	p	-20.54
9 He 2	3.3621	n	-20.66
9 Li 3	5.0379	β^-	-0.75
9 Be 4	6.4628		100.00%
9 B 5	6.2571	α	-17.91
9 C 6	4.3371	β^+	-0.90
10 Li 3	4.4922	n	-21.26
10 Be 4	6.4977	β^-	13.68
10 B 5	6.4751		19.90%
10 C 6	6.0320	β^+	1.29
10 N 7	3.5538	?	
11 Li 3	4.1499	β^-	-2.07
11 Be 4	5.9528	β^-	1.14
11 B 5	6.9277		80.10%
11 C 6	6.6764	β^+	3.09
11 n 7	5.3043	p	-21.05
12 Be 4	5.7208	β^-	-1.63
12 B 5	6.6313	β^-	-1.69
12 C 6	7.6801		98.90%
12 N 7	6.1701	β^+	-1.96
12 O 8	4.8778	p	-20.78
13 Be 4	5.1261	n	-21.14
13 B 5	6.4964	β^-	-1.76
13 C 6	7.4699		1.10%
13 N 7	7.2389	β^+	2.78
13 O 8	5.8121	β^+	-2.07
14 Be 4	4.9991	β^-	-2.36
14 B 5	6.1016	β^-	-1.86
14 C 6	7.5203	β^-	11.26
14 N 7	7.4756		99.63%
14 O 8	7.0524	β^+	1.85
14 F 9	5.1678	p	
15 B 5	5.8794	β^-	-1.98
15 C 6	7.1002	β^-	0.39
15 N 7	7.6995		0.37%
15 O 8	7.4637	β^+	2.09
15 F 9	6.4834	p	-21.18
15 Ne 10	4.7907	?	
16 B 5	5.5057	n	-9.70
16 C 6	6.9221	β^-	-0.13
16 N 7	7.3739	β^-	0.85
16 O 8	7.9762		99.76%
16 F 9	6.9637	p	-19.78
16 Ne 10	6.0831	p	-20.27
17 B 5	5.2697	β^-	-2.29
17 C 6	6.5578	β^-	-0.71
17 N 7	7.2862	β^-	0.62
17 O 8	7.7507		0.04%
17 F 9	7.5423	β^+	1.81

A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %	A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %
17 Ne 10	6.6414	β^+	-0.96	22 Al 13	6.7825	β^+	-1.15
17 Na 11	5.4961	?		22 Si 14	6.1115	β^+	-2.22
18 B 5	4.9472	?		23 N 7	6.1926	?	
18 C 6	6.4259	β^-	-1.02	23 O 8	7.1637	β^-	-1.09
18 N 7	7.0383	β^-	-0.20	23 F 9	7.6204	β^-	0.35
18 O 8	7.7671		0.20%	23 Ne 10	7.9552	β^-	1.57
18 F 9	7.6316	β^+	3.82	23 Na 11	8.1115		100.00%
18 Ne 10	7.3412	β^+	0.22	23 Mg 12	7.9011	β^+	1.05
18 Na 11	6.1867	?		23 Al 13	7.3349	β^+	-0.33
				23 Si 14	6.5616	?	
19 B 5	4.7410	?					
19 C 6	6.0962	β^-	-1.34	24 N 7	5.8831	?	
19 N 7	6.9483	β^-	-0.52	24 O 8	7.0199	β^-	-1.21
19 O 8	7.5665	β^-	1.43	24 F 9	7.4636	β^-	-0.47
19 F 9	7.7790		100.00%	24 Ne 10	7.9932	β^-	2.31
19 Ne 10	7.5674	β^+	1.24	24 Na 11	8.0635	β^-	4.73
19 Na 11	6.9379	p		24 Mg 12	8.2607		78.99%
19 Mg 12	5.8956	?		24 Al 13	7.6498	β^+	0.31
				24 Si 14	7.1668	β^+	-0.99
20 C 6	5.9586	β^-	-1.85	24 P 15	6.2492	?	
20 N 7	6.7092	β^-	-1.00				
20 O 8	7.5685	β^-	1.13	25 O 8	6.7352	?	
20 F 9	7.7201	β^-	1.04	25 F 9	7.3390	β^-	-1.23
20 Ne 10	8.0322		90.48%	25 Ne 10	7.8407	β^-	-0.22
20 Na 11	7.2988	β^+	-0.35	25 Na 11	8.1014	β^-	1.77
20 Mg 12	6.7234	β^+	-1.02	25 Mg 12	8.2235		10.00%
				25 Al 13	8.0211	β^+	0.86
21 C 6	5.6592	?		25 Si 14	7.4802	β^+	-0.66
21 N 7	6.6090	β^-	-1.07	25 P 15	6.8470	?	
21 O 8	7.3894	β^-	0.53				
21 F 9	7.7383	β^-	0.62	26 O 8	6.4782	?	
21 Ne 10	7.9717		0.27%	26 F 9	7.0971	?	
21 Na 11	7.7655	β^+	1.35	26 Ne 10	7.7539	β^-	-0.71
21 Mg 12	7.1047	β^+	-0.91	26 Na 11	8.0058	β^-	0.03
21 Al 13	6.3432	?		26 Mg 12	8.3339		11.01%
				26 Al 13	8.1498	β^+	13.35
22 C 6	5.4678	?		26 Si 14	7.9248	β^+	0.35
22 N 7	6.3642	β^-	-1.62	26 P 15	7.1979	β^+	-1.70
22 O 8	7.3648	β^-	0.35	26 S 16	6.5910	?	
22 F 9	7.6243	β^-	0.63				
22 Ne 10	8.0805		9.25%	27 F 9	6.8828	?	
22 Na 11	7.9157	β^+	7.91	27 Ne 10	7.5188	β^-	-1.49
22 Mg 12	7.6626	β^+	0.59	27 Na 11	7.9593	β^-	-0.52

A X Z	B/A (MeV)	$\rightarrow$	$\log t_{1/2}$ or %	A X Z	B/A (MeV)	$\rightarrow$	$\log t_{1/2}$ or %
27 Mg 12	8.2639	β^-	2.75	31 Ar 18	7.2527	β^+	-1.82
27 Al 13	8.3316		100.00%				
27 Si 14	8.1244	β^+	0.62	32 Ne 10	6.6651	?	
27 P 15	7.6646	β^+	-0.59	32 Na 11	7.2304	β^-	-1.88
27 S 16	6.9593	β^+	-1.68	32 Mg 12	7.8028	β^-	-0.92
				32 Al 13	8.0992	β^-	-1.48
28 F 9	6.6332	?		32 Si 14	8.4816	β^-	9.67
28 Ne 10	7.3891	β^-	-1.77	32 P 15	8.4641	β^-	6.09
28 Na 11	7.8009	β^-	-1.52	32 S 16	8.4931		95.02%
28 Mg 12	8.2724	β^-	4.88	32 Cl 17	8.0723	β^+	-0.53
28 Al 13	8.3099	β^-	2.13	32 Ar 18	7.6993	β^+	-1.01
28 Si 14	8.4477		92.23%	32 K 19	6.9687	?	
28 P 15	7.9080	β^+	-0.57				
28 S 16	7.4788	β^+	-0.90	33 Na 11	7.0375	β^-	-2.09
28 Cl 17	6.6479	?		33 Mg 12	7.6291	β^-	-1.05
				33 Al 13	8.0208	?	
29 F 9	6.4390	?		33 Si 14	8.3604	β^-	0.79
29 Ne 10	7.1801	β^-	-0.70	33 P 15	8.5138	β^-	6.34
29 Na 11	7.6843	β^-	-1.35	33 S 16	8.4976		0.75%
29 Mg 12	8.1152	β^-	0.11	33 Cl 17	8.3048	β^+	0.40
29 Al 13	8.3487	β^-	2.60	33 Ar 18	7.9289	β^+	-0.76
29 Si 14	8.4486		4.67%	33 K 19	7.4159	?	
29 P 15	8.2512	β^+	0.62				
29 S 16	7.7486	β^+	-0.73	34 Na 11	6.8621	β^-	-2.26
29 Cl 17	7.1595	?		34 Mg 12	7.5466	β^-	-1.70
				34 Al 13	7.8564	β^-	-1.22
30 Ne 10	7.0693	?		34 Si 14	8.3361	β^-	0.44
30 Na 11	7.4980	β^-	-1.32	34 P 15	8.4484	β^-	1.09
30 Mg 12	8.0545	β^-	-0.47	34 S 16	8.5835		4.21%
30 Al 13	8.2614	β^-	0.56	34 Cl 17	8.3990	β^+	0.18
30 Si 14	8.5207		3.10%	34 Ar 18	8.1977	β^+	-0.07
30 P 15	8.3535	β^+	2.18	34 K 19	7.6777	?	
30 S 16	8.1228	β^+	0.07	34 Ca 20	7.2243	?	
30 Cl 17	7.4799	?					
30 Ar 18	6.9325	p	-7.70	35 Na 11	6.6496	β^-	-2.82
				35 Mg 12	7.3062	?	
31 Ne 10	6.8241	?		35 Al 13	7.7824	β^-	-0.82
31 Na 11	7.3852	β^-	-1.77	35 Si 14	8.1687	β^-	-0.11
31 Mg 12	7.8722	β^-	-0.64	35 P 15	8.4462	β^-	1.67
31 Al 13	8.2256	β^-	-0.19	35 S 16	8.5379	β^-	6.88
31 Si 14	8.4583	β^-	3.97	35 Cl 17	8.5203		75.77%
31 P 15	8.4812		100.00%	35 Ar 18	8.3275	β^+	0.25
31 S 16	8.2819	β^+	0.41	35 K 19	7.9657	β^+	-0.72
31 Cl 17	7.8702	β^+	-0.82	35 Ca 20	7.4975	β^+	-1.30

A X Z	B/A (MeV)	$\rightarrow$	$\log t_{1/2}$ or %	A X Z	B/A (MeV)	$\rightarrow$	$\log t_{1/2}$ or %
				40 P 15	7.9864	β^-	-0.59
36 Mg 12	7.2296	?		40 S 16	8.3296	β^-	0.94
36 Al 13	7.6245	?		40 Cl 17	8.4278	β^-	1.91
36 Si 14	8.1115	β^-	-0.35	40 Ar 18	8.5953		99.60%
36 P 15	8.3079	β^-	0.75	40 K 19	8.5381	β^-	0.01%
36 S 16	8.5754		0.02%	40 Ca 20	8.5513	$\beta\beta$	96.94%
36 Cl 17	8.5219	β^-	12.98	40 Sc 21	8.1737	β^+	-0.74
36 Ar 18	8.5199	$\beta\beta$	0.34%	40 Ti 22	7.8623	β^+	-1.30
36 K 19	8.1424	β^+	-0.47	40 V 23	7.3632	?	
36 Ca 20	7.8155	β^+	-0.99				
36 Sc 21	7.2289	?		41 Si 14	7.5156	?	
				41 P 15	7.9032	β^-	-0.92
37 Al 13	7.5369	?		41 S 16	8.2197	?	
37 Si 14	7.9516	?		41 Cl 17	8.4137	β^-	1.58
37 P 15	8.2675	β^-	0.36	41 Ar 18	8.5344	β^-	3.82
37 S 16	8.4599	β^-	2.48	41 K 19	8.5761		6.73%
37 Cl 17	8.5703		24.23%	41 Ca 20	8.5467	EC	12.51
37 Ar 18	8.5272	EC	6.48	41 Sc 21	8.3692	β^+	-0.22
37 K 19	8.3398	β^+	0.09	41 Ti 22	8.0348	β^+	-1.10
37 Ca 20	8.0041	β^+	-0.74	41 V 23	7.6383	?	
37 Sc 21	7.5505	?					
				42 P 15	7.7899	β^-	-0.96
38 Al 13	7.3894	?		42 S 16	8.1838	β^-	-0.25
38 Si 14	7.8816	?		42 Cl 17	8.3496	β^-	0.83
38 P 15	8.1432	β^-	-0.19	42 Ar 18	8.5556	β^-	9.02
38 S 16	8.4488	β^-	4.01	42 K 19	8.5512	β^-	4.65
38 Cl 17	8.5055	β^-	3.35	42 Ca 20	8.6166		0.65%
38 Ar 18	8.6143		0.06%	42 Sc 21	8.4449	β^+	-0.17
38 K 19	8.4381	β^+	2.66	42 Ti 22	8.2596	β^+	-0.70
38 Ca 20	8.2401	β^+	-0.36	42 V 23	7.8374	?	
38 Sc 21	7.7689	?		42 Cr 24	7.4817	?	
38 Ti 22	7.3789	?					
				43 P 15	7.7267	β^-	-1.48
39 Si 14	7.7355	?		43 S 16	8.0705	β^-	-0.66
39 P 15	8.0948	β^-	-0.80	43 Cl 17	8.3208	β^-	0.52
39 S 16	8.3442	β^-	1.06	43 Ar 18	8.4875	β^-	2.51
39 Cl 17	8.4944	β^-	3.52	43 K 19	8.5766	β^-	4.90
39 Ar 18	8.5626	β^-	9.93	43 Ca 20	8.6007		0.14%
39 K 19	8.5570		93.26%	43 Sc 21	8.5308	β^+	4.15
39 Ca 20	8.3695	β^+	-0.07	43 Ti 22	8.3529	β^+	-0.29
39 Sc 21	8.0133	?		43 V 23	8.0720	β^+	-0.10
39 Ti 22	7.5984	β^+	-1.59	43 Cr 24	7.6843	β^+	-1.68
40 Si 14	7.6624	?		44 S 16	8.0341	β^-	-0.91

A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %	A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %
44 Cl 17	8.2234	β^-	-0.36	48 Ar 18	8.2617	?	
44 Ar 18	8.4845	β^-	2.85	48 K 19	8.4309	β^-	0.83
44 K 19	8.5474	β^-	3.12	48 Ca 20	8.6665	$\beta\beta$	0.19%
44 Ca 20	8.6582		2.09%	48 Sc 21	8.6560	β^-	5.20
44 Sc 21	8.5574	β^+	4.15	48 Ti 22	8.7229		73.80%
44 Ti 22	8.5335	EC	9.30	48 V 23	8.6230	β^+	6.14
44 V 23	8.2043	β^+	-1.05	48 Cr 24	8.5721	β^+	4.89
44 Cr 24	7.9522	β^+	-1.28	48 Mn 25	8.2740	β^+	-0.80
44 Mn 25	7.4814	?		48 Fe 26	8.0248	β^+	-1.36
				48 Co 27	7.5938	?	
45 S 16	7.9004	β^-	-1.09				
45 Cl 17	8.1960	β^-	-0.40	49 K 19	8.3867	β^-	0.10
45 Ar 18	8.4188	β^-	1.33	49 Ca 20	8.5947	β^-	2.72
45 K 19	8.5545	β^-	3.02	49 Sc 21	8.6861	β^-	3.54
45 Ca 20	8.6306	β^-	7.15	49 Ti 22	8.7110		5.50%
45 Sc 21	8.6189		100.00%	49 V 23	8.6828	EC	7.45
45 Ti 22	8.5557	β^+	4.05	49 Cr 24	8.6131	β^+	3.40
45 V 23	8.3798	β^+	-0.26	49 Mn 25	8.4397	β^+	-0.42
45 Cr 24	8.0854	β^+	-1.30	49 Fe 26	8.1579	β^+	-1.15
45 Mn 25	7.7503	?		49 Co 27	7.8419	?	
45 Fe 26	7.3179	?					
				50 K 19	8.2811	β^-	-0.33
46 Cl 17	8.1038	β^-	-0.65	50 Ca 20	8.5498	β^-	1.14
46 Ar 18	8.4113	β^-	0.92	50 Sc 21	8.6335	β^-	2.01
46 K 19	8.5182	β^-	2.02	50 Ti 22	8.7556		5.40%
46 Ca 20	8.6689	$\beta\beta$	0.00%	50 V 23	8.6958		0.25%
46 Sc 21	8.6220	β^-	6.86	50 Cr 24	8.7009	$\beta\beta$	4.34%
46 Ti 22	8.6564		8.00%	50 Mn 25	8.5326	β^+	-0.55
46 V 23	8.4861	β^+	-0.37	50 Fe 26	8.3539	β^+	-0.82
46 Cr 24	8.3038	β^+	-0.59	50 Co 27	7.9989	β^+	-1.36
46 Mn 25	7.9150	β^+	-1.39	50 Ni 28	7.7090	?	
46 Fe 26	7.6127	β^+	-1.70				
				51 Ca 20	8.4685	β^-	1.00
47 Cl 17	8.0272	β^-		51 Sc 21	8.5966	β^-	1.09
47 Ar 18	8.3229	β^-	-0.15	51 Ti 22	8.7089	β^-	2.54
47 K 19	8.5146	β^-	1.24	51 V 23	8.7420		99.75%
47 Ca 20	8.6393	β^-	5.59	51 Cr 24	8.7119	EC	6.38
47 Sc 21	8.6650	β^-	5.46	51 Mn 25	8.6336	β^+	3.44
47 Ti 22	8.6611		7.30%	51 Fe 26	8.4611	β^+	-0.52
47 V 23	8.5822	β^+	3.29	51 Co 27	8.1958	?	
47 Cr 24	8.4070	β^+	-0.30	51 Ni 28	7.8661	?	
47 Mn 25	8.1289	β^+	-1.00				
47 Fe 26	7.7794	β^+	-1.57	52 Ca 20	8.3956	β^-	0.66
				52 Sc 21	8.5334	β^-	0.91

A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %	A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %
52 Ti 22	8.6916	β^-	2.01	56 Cr 24	8.7233	β^-	2.55
52 V 23	8.7145	β^-	2.35	56 Mn 25	8.7382	β^-	3.97
52 Cr 24	8.7759		83.79%	56 Fe 26	8.7903		91.72%
52 Mn 25	8.6702	β^+	5.68	56 Co 27	8.6947	β^+	6.82
52 Fe 26	8.6096	β^+	4.47	56 Ni 28	8.6426	β^+	5.72
52 Co 27	8.3250	β^+	-1.74	56 Cu 29	8.3555	?	
52 Ni 28	8.0857	β^+	-1.42	56 Zn 30	8.1116	?	
52 Cu 29	7.6855	?		56 Ga 31	7.7229	?	
53 Ca 20	8.3025	β^-	-1.05	57 Ti 22	8.3528	β^-	-0.74
53 Sc 21	8.4928	?		57 V 23	8.5324	β^-	-0.49
53 Ti 22	8.6301	β^-	1.51	57 Cr 24	8.6611	β^-	1.32
53 V 23	8.7100	β^-	1.98	57 Mn 25	8.7367	β^-	1.93
53 Cr 24	8.7601		9.50%	57 Fe 26	8.7702		2.20%
53 Mn 25	8.7341	EC	14.07	57 Co 27	8.7418	EC	7.37
53 Fe 26	8.6487	β^+	2.71	57 Ni 28	8.6708	β^+	5.11
53 Co 27	8.4773	β^+	-0.62	57 Cu 29	8.5032	β^+	-0.70
53 Ni 28	8.2123	β^+	-1.35	57 Zn 30	8.2330	β^+	-1.40
53 Cu 29	7.8972	?		57 Ga 31	7.9338	?	
54 Sc 21	8.3967	?		58 V 23	8.4562	β^-	-0.70
54 Ti 22	8.5972	?		58 Cr 24	8.6423	β^-	0.85
54 V 23	8.6619	β^-	1.70	58 Mn 25	8.6979	β^-	0.48
54 Cr 24	8.7778		2.37%	58 Fe 26	8.7922		0.28%
54 Mn 25	8.7379	β^+	7.43	58 Co 27	8.7389	β^+	6.79
54 Fe 26	8.7363	$\beta\beta$	5.80%	58 Ni 28	8.7320	$\beta\beta$	68.08%
54 Co 27	8.5691	β^+	-0.71	58 Cu 29	8.5708	β^+	0.51
54 Ni 28	8.3917	β^+		58 Zn 30	8.3959	β^+	-1.19
54 Cu 29	8.0529	?		58 Ga 31	8.0667	?	
54 Zn 30	7.7583	?		58 Ge 32	7.7841	?	
55 Sc 21	8.2909	?		59 V 23	8.4089	β^-	-0.89
55 Ti 22	8.5167	β^-	-0.49	59 Cr 24	8.5628	β^-	-0.13
55 V 23	8.6378	β^-	0.82	59 Mn 25	8.6800	β^-	0.66
55 Cr 24	8.7318	β^-	2.32	59 Fe 26	8.7547	β^-	6.59
55 Mn 25	8.7649		100.00%	59 Co 27	8.7679		100.00%
55 Fe 26	8.7465	EC	7.94	59 Ni 28	8.7365	β^+	12.38
55 Co 27	8.6695	β^+	4.80	59 Cu 29	8.6419	β^+	1.91
55 Ni 28	8.4972	β^+	-0.67	59 Zn 30	8.4745	β^+	-0.74
55 Cu 29	8.2428	β^+		59 Ga 31	8.2386	?	
55 Zn 30	7.9159	?		59 Ge 32	7.9351	?	
56 Ti 22	8.4628	β^-	-0.80	60 V 23	8.3226	β^-	-0.70
56 V 23	8.5742	β^-	-0.64	60 Cr 24	8.5388	β^-	-0.24

A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %	A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %
60 Mn 25	8.6249	β^-	1.71	64 Co 27	8.6755	β^-	-0.52
60 Fe 26	8.7558	β^-	13.67	64 Ni 28	8.7774		0.93%
60 Co 27	8.7467	β^-	8.22	64 Cu 29	8.7390	β^+	4.66
60 Ni 28	8.7807		26.22%	64 Zn 30	8.7358	$\beta\beta$	48.60%
60 Cu 29	8.6655	β^+	3.15	64 Ga 31	8.6117	β^+	2.20
60 Zn 30	8.5832	β^+	2.16	64 Ge 32	8.5305	β^+	1.80
60 Ga 31	8.3338	?		64 As 33	8.2875	?	
60 Ge 32	8.1169	?					
60 As 33	7.7477	?		65 Mn 25	8.3995	β^-	-0.96
				65 Fe 26	8.5474	β^-	-0.40
61 Cr 24	8.4646	β^-	-0.57	65 Co 27	8.6566	β^-	0.08
61 Mn 25	8.5961	β^-	-0.15	65 Ni 28	8.7362	β^-	3.96
61 Fe 26	8.7037	β^-	2.56	65 Cu 29	8.7570		30.83%
61 Co 27	8.7561	β^-	3.77	65 Zn 30	8.7242	β^+	7.32
61 Ni 28	8.7649		1.14%	65 Ga 31	8.6621	β^+	2.96
61 Cu 29	8.7155	β^+	4.08	65 Ge 32	8.5540	β^+	1.49
61 Zn 30	8.6102	β^+	1.95	65 As 33	8.3981	β^+	-0.72
61 Ga 31	8.4499	β^+	-0.82	65 Se 34	8.1685	β^+	
61 Ge 32	8.2139	β^+	-1.40				
61 As 33	7.9440	?		66 Fe 26	8.5255	β^-	-0.36
				66 Co 27	8.6005	β^-	-0.63
62 Cr 24	8.4325	β^-	-0.72	66 Ni 28	8.7399	β^-	5.29
62 Mn 25	8.5376	β^-	-0.06	66 Cu 29	8.7314	β^-	2.49
62 Fe 26	8.6932	β^-	1.83	66 Zn 30	8.7596		27.90%
62 Co 27	8.7214	β^-	1.95	66 Ga 31	8.6693	β^+	4.53
62 Ni 28	8.7945		3.63%	66 Ge 32	8.6257	β^+	3.91
62 Cu 29	8.7182	β^+	2.77	66 As 33	8.4691	β^+	-1.02
62 Zn 30	8.6793	β^+	4.52	66 Se 34	8.3004	β^+	
62 Ga 31	8.5188	β^+	-0.94				
62 Ge 32	8.3489	β^+		67 Fe 26	8.4629	β^-	-0.33
62 As 33	8.0575	?		67 Co 27	8.5817	β^-	-0.38
				67 Ni 28	8.6958	β^-	1.32
63 Mn 25	8.5030	β^-	-0.60	67 Cu 29	8.7372	β^-	5.35
63 Fe 26	8.6296	β^-	0.79	67 Zn 30	8.7341		4.10%
63 Co 27	8.7176	β^-	1.44	67 Ga 31	8.7075	EC	5.45
63 Ni 28	8.7634	β^-	9.50	67 Ge 32	8.6328	β^+	3.05
63 Cu 29	8.7521		69.17%	67 As 33	8.5314	β^+	1.63
63 Zn 30	8.6862	β^+	3.36	67 Se 34	8.3682	β^+	-1.22
63 Ga 31	8.5862	β^+	1.51				
63 Ge 32	8.4185	β^+	-1.02	68 Fe 26	8.4227	β^-	-1.00
63 As 33	8.1984	?		68 Co 27	8.5229	β^-	-0.74
				68 Ni 28	8.6828	β^-	1.28
64 Mn 25	8.4392	β^-	-0.85	68 Cu 29	8.7015	β^-	1.49
64 Fe 26	8.6113	β^-	0.30	68 Zn 30	8.7556		18.80%

A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %	A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %
68 Ga 31	8.7012	β^+	3.61	72 Se 34	8.6449	EC	5.86
68 Ge 32	8.6881	EC	7.37	72 Br 35	8.5130	β^+	1.90
68 As 33	8.5575	β^+	2.18	72 Kr 36	8.4321	β^+	1.24
68 Se 34	8.4764	β^+	1.55	72 Rb 37	8.1987	?	
68 Br 35	8.2406	p	-5.82				
				73 Ni 28	8.4607	β^-	-0.15
69 Co 27	8.5050	β^-	-0.57	73 Cu 29	8.5709	β^-	0.59
69 Ni 28	8.6289	β^-	1.06	73 Zn 30	8.6458	β^-	1.37
69 Cu 29	8.6953	β^-	2.23	73 Ga 31	8.6939	β^-	4.24
69 Zn 30	8.7227	β^-	3.53	73 Ge 32	8.7050		7.73%
69 Ga 31	8.7245		60.11%	73 As 33	8.6897	EC	6.84
69 Ge 32	8.6809	β^+	5.15	73 Se 34	8.6414	β^+	4.41
69 As 33	8.6114	β^+	2.96	73 Br 35	8.5669	β^+	2.31
69 Se 34	8.5017	β^+	1.44	73 Kr 36	8.4648	β^+	1.43
69 Br 35	8.3510	?		73 Rb 37	8.3085	?	
70 Co 27	8.4374	β^-	-0.82	74 Ni 28	8.4338	β^-	-0.27
70 Ni 28	8.6082	?		74 Cu 29	8.5191	β^-	0.20
70 Cu 29	8.6466	β^-	0.65	74 Zn 30	8.6421	β^-	1.98
70 Zn 30	8.7297	$\beta\beta$	0.60%	74 Ga 31	8.6632	β^-	2.69
70 Ga 31	8.7092	β^-	3.10	74 Ge 32	8.7252		35.94%
70 Ge 32	8.7217		21.23%	74 As 33	8.6800	β^-	6.19
70 As 33	8.6217	β^+	3.50	74 Se 34	8.6877	$\beta\beta$	0.89%
70 Se 34	8.5762	β^+	3.39	74 Br 35	8.5838	β^+	3.18
70 Br 35	8.4226	β^+	-1.10	74 Kr 36	8.5308	β^+	2.84
70 Kr 36	8.2543	?		74 Rb 37	8.3791	β^+	-1.19
71 Co 27	8.4071	β^-	-0.68	75 Ni 28	8.3681	β^-	-0.22
71 Ni 28	8.5500	β^-	0.27	75 Cu 29	8.4965	β^-	0.09
71 Cu 29	8.6358	β^-	1.29	75 Zn 30	8.5913	β^-	1.01
71 Zn 30	8.6889	β^-	2.17	75 Ga 31	8.6608	β^-	2.10
71 Ga 31	8.7175		39.89%	75 Ge 32	8.6956	β^-	3.70
71 Ge 32	8.7033	EC	5.99	75 As 33	8.7009		100.00%
71 As 33	8.6639	β^+	5.37	75 Se 34	8.6789	EC	7.01
71 Se 34	8.5905	β^+	2.45	75 Br 35	8.6281	β^+	3.76
71 Br 35	8.4827	β^+	1.33	75 Kr 36	8.5523	β^+	2.41
71 Kr 36	8.3239	β^+	-1.19	75 Rb 37	8.4483	β^+	1.28
				75 Sr 38	8.2969	β^+	-1.15
72 Ni 28	8.5265	β^-	0.32				
72 Cu 29	8.5882	β^-	0.82	76 Ni 28	8.3381	β^-	-0.62
72 Zn 30	8.6915	β^-	5.22	76 Cu 29	8.4404	β^-	-0.19
72 Ga 31	8.6870	β^-	4.71	76 Zn 30	8.5789	β^-	0.76
72 Ge 32	8.7317		27.66%	76 Ga 31	8.6233	β^-	1.51
72 As 33	8.6604	β^+	4.97	76 Ge 32	8.7052	$\beta\beta$	7.44%

A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %	A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %
76 As 33	8.6828	β^-	4.97				
76 Se 34	8.7115		9.36%	80 Zn 30	8.4252	β^-	-0.26
76 Br 35	8.6359	β^+	4.77	80 Ga 31	8.5065	β^-	0.23
76 Kr 36	8.6083	β^+	4.73	80 Ge 32	8.6265	β^-	1.47
76 Rb 37	8.4862	β^+	1.56	80 As 33	8.6501	β^-	1.18
76 Sr 38	8.3958	β^+	0.95	80 Se 34	8.7108	$\beta\beta$	49.61%
				80 Br 35	8.6777	β^-	3.03
77 Ni 28	8.2700	?		80 Kr 36	8.6929		2.25%
77 Cu 29	8.4144	β^-	-0.33	80 Rb 37	8.6116	β^+	1.53
77 Zn 30	8.5276	β^-	0.32	80 Sr 38	8.5785	β^+	3.80
77 Ga 31	8.6119	β^-	1.12	80 Y 39	8.4819	β^+	1.54
77 Ge 32	8.6710	β^-	4.61	80 Zr 40	8.3719	?	
77 As 33	8.6960	β^-	5.15				
77 Se 34	8.6947		7.63%	81 Zn 30	8.3510	β^-	-0.54
77 Br 35	8.6668	β^+	5.31	81 Ga 31	8.4877	β^-	0.09
77 Kr 36	8.6168	β^+	3.65	81 Ge 32	8.5808	β^-	0.88
77 Rb 37	8.5373	β^+	2.35	81 As 33	8.6480	β^-	1.52
77 Sr 38	8.4381	β^+	0.95	81 Se 34	8.6860	β^-	3.05
77 Y 39	8.2845	β^+		81 Br 35	8.6959		49.31%
				81 Kr 36	8.6828	EC	12.86
78 Ni 28	8.2359	β^-		81 Rb 37	8.6455	β^+	4.22
78 Cu 29	8.3556	β^-	-0.47	81 Sr 38	8.5873	β^+	3.13
78 Zn 30	8.5040	β^-	0.17	81 Y 39	8.5096	β^+	1.85
78 Ga 31	8.5766	β^-	0.71	81 Zr 40	8.4116	β^+	1.18
78 Ge 32	8.6717	β^-	3.72				
78 As 33	8.6739	β^-	3.74	82 Zn 30	8.2981	β^-	
78 Se 34	8.7178		23.78%	82 Ga 31	8.4212	β^-	-0.22
78 Br 35	8.6620	β^+	2.59	82 Ge 32	8.5653	β^-	0.66
78 Kr 36	8.6610	$\beta\beta$	0.35%	82 As 33	8.6130	β^-	1.28
78 Rb 37	8.5583	β^+	3.03	82 Se 34	8.6932	$\beta\beta$	8.73%
78 Sr 38	8.5001	β^+	2.18	82 Br 35	8.6825	β^-	5.10
78 Y 39	8.3549	?		82 Kr 36	8.7106		11.60%
				82 Rb 37	8.6474	β^+	1.88
79 Cu 29	8.3247	β^-	-0.73	82 Sr 38	8.6357	EC	6.34
79 Zn 30	8.4570	β^-	0.00	82 Y 39	8.5308	β^+	0.98
79 Ga 31	8.5553	β^-	0.45	82 Zr 40	8.4725	β^+	1.51
79 Ge 32	8.6340	β^-	1.28	82 Nb 41	8.3262	?	
79 As 33	8.6766	β^-	2.73				
79 Se 34	8.6956	β^-	13.55	83 Ga 31	8.3754	β^-	-0.51
79 Br 35	8.6876		50.69%	83 Ge 32	8.5047	β^-	0.27
79 Kr 36	8.6571	β^+	5.10	83 As 33	8.6022	β^-	1.13
79 Rb 37	8.6010	β^+	3.14	83 Se 34	8.6586	β^-	3.13
79 Sr 38	8.5238	β^+	2.13	83 Br 35	8.6933	β^-	3.94
79 Y 39	8.4238	β^+	1.17	83 Kr 36	8.6956		11.50%

A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %	A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %
83 Rb 37	8.6752	EC	6.87	87 As 33	8.4215	β^-	-0.32
83 Sr 38	8.6384	β^+	5.07	87 Se 34	8.5308	β^-	0.72
83 Y 39	8.5751	β^+	2.63	87 Br 35	8.6055	β^-	1.75
83 Zr 40	8.4950	β^+	1.64	87 Kr 36	8.6752	β^-	3.66
83 Nb 41	8.3952	β^+	0.61	87 Rb 37	8.7109	β^-	27.83%
				87 Sr 38	8.7052		7.00%
84 Ga 31	8.3111	β^-	-1.07	87 Y 39	8.6748	β^+	5.46
84 Ge 32	8.4685	β^-	-0.02	87 Zr 40	8.6237	β^+	3.78
84 As 33	8.5506	β^-	0.65	87 Nb 41	8.5553	β^+	2.19
84 Se 34	8.6588	β^-	2.27	87 Mo 42	8.4717	β^+	1.13
84 Br 35	8.6712	β^-	3.28	87 Tc 43	8.3642	?	
84 Kr 36	8.7173		57.00%				
84 Rb 37	8.6761	β^-	6.45	88 As 33	8.3648	?	
84 Sr 38	8.6774	$\beta\beta$	0.56%	88 Se 34	8.4949	β^-	0.18
84 Y 39	8.5918	β^+	0.66	88 Br 35	8.5639	β^-	1.21
84 Zr 40	8.5499	β^+	3.19	88 Kr 36	8.6568	β^-	4.01
84 Nb 41	8.4261	β^+	1.08	88 Rb 37	8.6810	β^-	3.03
84 Mo 42	8.3445	β^+		88 Sr 38	8.7326		82.58%
				88 Y 39	8.6825	β^+	6.96
85 Ge 32	8.4048	β^-	-0.27	88 Zr 40	8.6660	EC	6.86
85 As 33	8.5149	β^-	0.31	88 Nb 41	8.5713	β^+	2.94
85 Se 34	8.6105	β^-	1.50	88 Mo 42	8.5241	β^+	2.68
85 Br 35	8.6740	β^-	2.24	88 Tc 43	8.4000	β^+	0.81
85 Kr 36	8.6985	β^-	8.53				
85 Rb 37	8.6974		72.17%	89 Se 34	8.4421	β^-	-0.39
85 Sr 38	8.6757	β^+	6.75	89 Br 35	8.5340	β^-	0.64
85 Y 39	8.6282	β^+	3.98	89 Kr 36	8.6169	β^-	2.28
85 Zr 40	8.5638	β^+	2.67	89 Rb 37	8.6641	β^-	2.96
85 Nb 41	8.4840	β^+	1.32	89 Sr 38	8.7059	β^-	6.64
85 Mo 42	8.3796	?		89 Y 39	8.7139		100.00%
				89 Zr 40	8.6733	β^+	5.45
86 Ge 32	8.3622	?		89 Nb 41	8.6163	β^+	3.84
86 As 33	8.4618	β^-	-0.02	89 Mo 42	8.5449	β^+	2.09
86 Se 34	8.5822	β^-	1.18	89 Tc 43	8.4517	β^+	1.11
86 Br 35	8.6324	β^-	1.74	89 Ru 44	8.3532	?	
86 Kr 36	8.7120	$\beta\beta$	17.30%				
86 Rb 37	8.6969	β^-	6.21	90 Se 34	8.4028	?	
86 Sr 38	8.7084		9.86%	90 Br 35	8.4850	β^-	0.28
86 Y 39	8.6384	β^+	4.73	90 Kr 36	8.5913	β^-	1.51
86 Zr 40	8.6122	β^+	4.77	90 Rb 37	8.6314	β^-	2.20
86 Nb 41	8.5103	β^+	1.94	90 Sr 38	8.6959	β^-	8.96
86 Mo 42	8.4453	β^+	1.29	90 Y 39	8.6933	β^-	5.36
86 Tc 43	8.2980	?		90 Zr 40	8.7099		51.45%
				90 Nb 41	8.6333	β^+	4.72

A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %	A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %
90 Mo 42	8.5970	β^+	4.30	94 Zr 40	8.6668	$\beta\beta$	17.38%
90 Tc 43	8.4896	β^+	1.69	94 Nb 41	8.6489	β^-	11.81
90 Ru 44	8.4156	β^+	1.04	94 Mo 42	8.6623		9.25%
				94 Tc 43	8.6087	β^+	4.25
91 Se 34	8.3382	β^-	-0.57	94 Ru 44	8.5834	β^+	3.49
91 Br 35	8.4468	β^-	-0.27	94 Rh 45	8.4727	β^+	1.85
91 Kr 36	8.5459	β^-	0.93	94 Pd 46	8.3943	β^+	0.95
91 Rb 37	8.6080	β^-	1.77				
91 Sr 38	8.6638	β^-	4.54	95 Kr 36	8.3658	β^-	-0.11
91 Y 39	8.6849	β^-	6.70	95 Rb 37	8.4599	β^-	-0.42
91 Zr 40	8.6933		11.22%	95 Sr 38	8.5495	β^-	1.38
91 Nb 41	8.6709	β^+	10.33	95 Y 39	8.6053	β^-	2.79
91 Mo 42	8.6136	β^+	2.97	95 Zr 40	8.6436	β^-	6.74
91 Tc 43	8.5366	β^+	2.27	95 Nb 41	8.6472	β^-	6.48
91 Ru 44	8.4467	β^+	0.95	95 Mo 42	8.6487		15.92%
				95 Tc 43	8.6227	β^+	4.86
92 Br 35	8.3892	β^-	-0.46	95 Ru 44	8.5873	β^+	3.77
92 Kr 36	8.5133	β^-	0.26	95 Rh 45	8.5253	β^+	2.48
92 Rb 37	8.5699	β^-	0.65	95 Pd 46	8.4309	β^+	
92 Sr 38	8.6495	β^-	3.99				
92 Y 39	8.6617	β^-	4.10	96 Kr 36	8.3328	?	
92 Zr 40	8.6926		17.15%	96 Rb 37	8.4076	β^-	-0.70
92 Nb 41	8.6623	β^+	15.04	96 Sr 38	8.5219	β^-	0.03
92 Mo 42	8.6577	$\beta\beta$	14.84%	96 Y 39	8.5697	β^-	0.73
92 Tc 43	8.5637	β^+	2.40	96 Zr 40	8.6354	$\beta\beta$	2.80%
92 Ru 44	8.5059	β^+	2.34	96 Nb 41	8.6289	β^-	4.92
92 Rh 45	8.3773	?		96 Mo 42	8.6540		16.68%
				96 Tc 43	8.6148	β^+	5.57
93 Br 35	8.3468	β^-	-0.99	96 Ru 44	8.6093	$\beta\beta$	5.52%
93 Kr 36	8.4577	β^-	0.11	96 Rh 45	8.5340	β^+	2.77
93 Rb 37	8.5418	β^-	0.77	96 Pd 46	8.4899	β^+	2.09
93 Sr 38	8.6136	β^-	2.65	96 Ag 47	8.3609	β^+	0.71
93 Y 39	8.6491	β^-	4.56				
93 Zr 40	8.6716	β^-	13.68	97 Rb 37	8.3747	β^-	-0.77
93 Nb 41	8.6642		100.00%	97 Sr 38	8.4741	β^-	-0.37
93 Mo 42	8.6514	EC	11.10	97 Y 39	8.5430	β^-	0.57
93 Tc 43	8.6086	β^+	4.00	97 Zr 40	8.6039	β^-	4.78
93 Ru 44	8.5320	β^+	1.78	97 Nb 41	8.6232	β^-	3.64
93 Rh 45	8.4366	?		97 Mo 42	8.6351		9.55%
				97 Tc 43	8.6237	EC	13.91
94 Kr 36	8.4230	β^-	-0.70	97 Ru 44	8.6041	β^+	5.40
94 Rb 37	8.4924	β^-	0.43	97 Rh 45	8.5598	β^+	3.26
94 Sr 38	8.5937	β^-	1.88	97 Pd 46	8.5023	β^+	2.27
94 Y 39	8.6228	β^-	3.05	97 Ag 47	8.4221	β^+	1.28

A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %	A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %
				101 Sr 38	8.3256	β^-	-0.93
98 Rb 37	8.3297	β^-	-0.94	101 Y 39	8.4119	β^-	-0.35
98 Sr 38	8.4477	β^-	-0.19	101 Zr 40	8.4888	β^-	0.36
98 Y 39	8.4991	β^-	-0.26	101 Nb 41	8.5354	β^-	0.85
98 Zr 40	8.5812	β^-	1.49	101 Mo 42	8.5728	β^-	2.94
98 Nb 41	8.5963	β^-	0.46	101 Tc 43	8.5931	β^-	2.93
98 Mo 42	8.6351	ββ	24.13%	101 Ru 44	8.6013		17.00%
98 Tc 43	8.6100	β^-	14.12	101 Rh 45	8.5882	EC	8.02
98 Ru 44	8.6203		1.88%	101 Pd 46	8.5608	β^+	4.48
98 Rh 45	8.5607	β^+	2.72	101 Ag 47	8.5115	β^+	2.82
98 Pd 46	8.5336	β^+	3.03	101 Cd 48	8.4495	β^+	1.91
98 Ag 47	8.4397	β^+	1.67	101 In 49	8.3691	β^+	1.18
98 Cd 48	8.3764	β^+	0.96	101 Sn 50	8.2737	β^+	0.48
99 Rb 37	8.2933	β^-	-1.30	102 Sr 38	8.3002	β^-	-1.16
99 Sr 38	8.3990	β^-	-0.57	102 Y 39	8.3790	β^-	-0.44
99 Y 39	8.4723	β^-	0.17	102 Zr 40	8.4679	β^-	0.46
99 Zr 40	8.5408	β^-	0.32	102 Nb 41	8.5054	β^-	0.11
99 Nb 41	8.5789	β^-	1.18	102 Mo 42	8.5684	β^-	2.83
99 Mo 42	8.6078	β^-	5.37	102 Tc 43	8.5706	β^-	0.72
99 Tc 43	8.6136	β^-	12.82	102 Ru 44	8.6074		31.60%
99 Ru 44	8.6086		12.70%	102 Rh 45	8.5769	β^-	7.25
99 Rh 45	8.5795	β^+	6.14	102 Pd 46	8.5805	ββ	1.02%
99 Pd 46	8.5376	β^+	3.11	102 Ag 47	8.5148	β^+	2.89
99 Ag 47	8.4748	β^+	2.09	102 Cd 48	8.4817	β^+	2.52
99 Cd 48	8.3976	β^+	1.20	102 In 49	8.3868	β^+	1.34
99 In 49	8.2994	?		102 Sn 50	8.3226	β^+	0.65
100 Rb 37	8.2488	β^-	-1.29	103 Y 39	8.3439	β^-	-0.64
100 Sr 38	8.3762	β^-	-0.69	103 Zr 40	8.4313	β^-	0.11
100 Y 39	8.4392	β^-	-0.13	103 Nb 41	8.4912	β^-	0.18
100 Zr 40	8.5244	β^-	0.85	103 Mo 42	8.5373	β^-	1.83
100 Nb 41	8.5500	β^-	0.18	103 Tc 43	8.5661	β^-	1.73
100 Mo 42	8.6046	ββ	9.63%	103 Ru 44	8.5843	β^-	6.53
100 Tc 43	8.5951	β^-	1.20	103 Rh 45	8.5841		100.00%
100 Ru 44	8.6193		12.60%	103 Pd 46	8.5712	EC	6.17
100 Rh 45	8.5752	β^+	4.87	103 Ag 47	8.5375	β^+	3.60
100 Pd 46	8.5637	EC	5.50	103 Cd 48	8.4897	β^+	2.64
100 Ag 47	8.4851	β^+	2.08	103 In 49	8.4234	β^+	1.81
100 Cd 48	8.4384	β^+	1.69	103 Sn 50	8.3415	β^+	0.85
100 In 49	8.3253	β^+	0.85				
100 Sn 50	8.2448	β^+	-0.03	104 Y 39	8.3059	?	
				104 Zr 40	8.4083	β^-	0.08
101 Rb 37	8.2164	β^-	-1.49	104 Nb 41	8.4574	β^-	0.68

A X *Z*	B/A (MeV)	→	log $t_{1/2}$ or %	*A* X *Z*	B/A (MeV)	→	log $t_{1/2}$ or %
104 Mo 42	8.5278	β^-	1.78	107 Ag 47	8.5539		51.84%
104 Tc 43	8.5410	β^-	3.04	107 Cd 48	8.5333	β^+	4.37
104 Ru 44	8.5874	$\beta\beta$	18.70%	107 In 49	8.4940	β^+	3.29
104 Rh 45	8.5689	β^-	1.63	107 Sn 50	8.4400	β^+	2.24
104 Pd 46	8.5848		11.14%	107 Sb 51	8.3587	?	
104 Ag 47	8.5362	β^+	3.62	107 Te 52	8.2567	α	-2.51
104 Cd 48	8.5177	β^+	3.54				
104 In 49	8.4341	β^+	2.03	108 Nb 41	8.3391	β^-	-0.71
104 Sn 50	8.3832	β^+	1.32	108 Mo 42	8.4226	β^-	0.04
104 Sb 51	8.2552	β^+	-0.36	108 Tc 43	8.4629	β^-	0.71
				108 Ru 44	8.5272	β^-	2.44
105 Zr 40	8.3672	β^-	-0.22	108 Rh 45	8.5325	β^-	1.23
105 Nb 41	8.4406	β^-	0.47	108 Pd 46	8.5670		26.46%
105 Mo 42	8.4950	β^-	1.55	108 Ag 47	8.5420	β^-	2.15
105 Tc 43	8.5347	β^-	2.66	108 Cd 48	8.5500	$\beta\beta$	0.89%
105 Ru 44	8.5619	β^-	4.20	108 In 49	8.4951	β^+	3.54
105 Rh 45	8.5727	β^-	5.10	108 Sn 50	8.4685	β^+	2.79
105 Pd 46	8.5706		22.33%	108 Sb 51	8.3732	β^+	0.87
105 Ag 47	8.5504	β^+	6.55	108 Te 52	8.3028	β^+	0.32
105 Cd 48	8.5168	β^+	3.52	108 I 53	8.1741	α	-1.44
105 In 49	8.4632	β^+	2.48				
105 Sn 50	8.3962	β^+	1.49	109 Mo 42	8.3878	β^-	-0.28
105 Sb 51	8.3000	β^+	0.05	109 Tc 43	8.4465	β^-	-0.06
				109 Ru 44	8.4973	β^-	1.54
106 Zr 40	8.3439	?		109 Rh 45	8.5283	β^-	1.90
106 Nb 41	8.4006	β^-	0.01	109 Pd 46	8.5449	β^-	4.69
106 Mo 42	8.4807	β^-	0.92	109 Ag 47	8.5479		48.16%
106 Tc 43	8.5066	β^-	1.55	109 Cd 48	8.5388	EC	7.60
106 Ru 44	8.5610	β^-	7.51	109 In 49	8.5131	β^+	4.18
106 Rh 45	8.5539	β^-	1.47	109 Sn 50	8.4706	β^+	3.03
106 Pd 46	8.5800		27.33%	109 Sb 51	8.4049	β^+	1.23
106 Ag 47	8.5446	β^+	3.16	109 Te 52	8.3181	β^+	0.66
106 Cd 48	8.5391	$\beta\beta$	1.25%	109 I 53	8.2191	p	-4.00
106 In 49	8.4702	β^+	2.57				
106 Sn 50	8.4327	β^+	2.06	110 Mo 42	8.3696	β^-	-0.52
106 Sb 51	8.3260	?		110 Tc 43	8.4142	β^-	-0.04
106 Te 52	8.2347	α	-4.22	110 Ru 44	8.4869	β^-	1.16
				110 Rh 45	8.5054	β^-	0.51
107 Nb 41	8.3794	β^-	-0.48	110 Pd 46	8.5473	$\beta\beta$	11.72%
107 Mo 42	8.4459	β^-	0.54	110 Ag 47	8.5321	β^-	1.39
107 Tc 43	8.4962	β^-	1.33	110 Cd 48	8.5513		12.49%
107 Ru 44	8.5339	β^-	2.35	110 In 49	8.5089	β^+	4.25
107 Rh 45	8.5541	β^-	3.11	110 Sn 50	8.4960	EC	4.17
107 Pd 46	8.5609	β^-	14.31	110 Sb 51	8.4069	β^+	1.36

A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %	A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %
110 Te 52	8.3586	β^+	1.27				
110 I 53	8.2479	β^+	-0.19	114 Ru 44	8.3912	β^-	-0.28
110 Xe 54	8.1572	β^+	-6.22	114 Rh 45	8.4379	β^-	0.27
				114 Pd 46	8.4880	β^-	2.16
111 Tc 43	8.3972	β^-	-0.52	114 Ag 47	8.4939	β^-	0.66
111 Ru 44	8.4530	β^-	0.33	114 Cd 48	8.5316	$\beta\beta$	28.73%
111 Rh 45	8.4955	β^-	1.04	114 In 49	8.5120	β^-	1.86
111 Pd 46	8.5221	β^-	3.15	114 Sn 50	8.5225		0.65%
111 Ag 47	8.5348	β^-	5.81	114 Sb 51	8.4641	β^+	2.32
111 Cd 48	8.5371		12.80%	114 Te 52	8.4296	β^+	2.96
111 In 49	8.5222	EC	5.38	114 I 53	8.3462	β^+	0.32
111 Sn 50	8.4932	β^+	3.33	114 Xe 54	8.2879	β^+	1.00
111 Sb 51	8.4459	β^+	1.88	114 Cs 55	8.1772	β^+	-0.24
111 Te 52	8.3667	β^+	1.29				
111 I 53	8.2829	β^+	0.40	115 Ru 44	8.3527	β^-	-0.40
111 Xe 54	8.1806	β^+	-0.13	115 Rh 45	8.4122	β^-	0.00
				115 Pd 46	8.4575	β^-	1.40
112 Tc 43	8.3595	β^-	-0.55	115 Ag 47	8.4906	β^-	3.08
112 Ru 44	8.4391	β^-	0.24	115 Cd 48	8.5108	β^-	5.28
112 Rh 45	8.4725	β^-	0.32	115 In 49	8.5165	β^-	95.70%
112 Pd 46	8.5209	β^-	4.88	115 Sn 50	8.5141		0.34%
112 Ag 47	8.5164	β^-	4.05	115 Sb 51	8.4809	β^+	3.29
112 Cd 48	8.5448		24.13%	115 Te 52	8.4338	β^+	2.54
112 In 49	8.5147	β^-	2.95	115 I 53	8.3688	β^+	1.89
112 Sn 50	8.5136	$\beta\beta$	0.97%	115 Xe 54	8.2955	β^+	1.26
112 Sb 51	8.4437	β^+	1.71	115 Cs 55	8.2161	β^+	0.15
112 Te 52	8.3979	β^+	2.08	115 Ba 56	8.1139	β^+	-0.40
112 I 53	8.3002	β^+	0.53				
112 Xe 54	8.2293	β^+	0.43	116 Ru 44	8.3363	?	
112 Cs 55	8.1004	p	-3.30	116 Rh 45	8.3881	β^-	-0.17
				116 Pd 46	8.4503	β^-	1.07
113 Tc 43	8.3397	β^-	-0.89	116 Ag 47	8.4661	β^-	2.21
113 Ru 44	8.4052	β^-	-0.10	116 Cd 48	8.5124	$\beta\beta$	7.49%
113 Rh 45	8.4570	β^-	0.45	116 In 49	8.5016	β^-	1.15
113 Pd 46	8.4935	β^-	1.97	116 Sn 50	8.5231		14.53%
113 Ag 47	8.5161	β^-	4.29	116 Sb 51	8.4758	β^+	2.98
113 Cd 48	8.5270	β^-	12.22%	116 Te 52	8.4561	β^+	3.95
113 In 49	8.5229		4.30%	116 I 53	8.3826	β^+	0.46
113 Sn 50	8.5068	β^+	7.00	116 Xe 54	8.3384	β^+	1.77
113 Sb 51	8.4653	β^+	2.60	116 Cs 55	8.2386	β^+	0.58
113 Te 52	8.4083	β^+	2.01	116 Ba 56	8.1619	β^+	-0.52
113 I 53	8.3338	β^+	0.82				
113 Xe 54	8.2467	β^+	0.44	117 Rh 45	8.3647	β^-	-0.36
113 Cs 55	8.1479	p	-4.77	117 Pd 46	8.4178	β^-	0.63

A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %	A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %
117 Ag 47	8.4600	β^-	1.86	120 Sb 51	8.4757	β^+	2.98
117 Cd 48	8.4890	β^-	3.95	120 Te 52	8.4773	$\beta\beta$	0.10%
117 In 49	8.5039	β^-	3.41	120 I 53	8.4240	β^+	3.69
117 Sn 50	8.5096		7.68%	120 Xe 54	8.4011	β^+	3.38
117 Sb 51	8.4879	β^+	4.00	120 Cs 55	8.3286	β^+	1.81
117 Te 52	8.4510	β^+	3.57	120 Ba 56	8.2804	β^+	1.51
117 I 53	8.4045	β^+	2.12	120 La 57	8.1804	β^+	0.45
117 Xe 54	8.3428	β^+	1.79				
117 Cs 55	8.2718	β^+	0.92	121 Pd 46	8.3268	?	
117 Ba 56	8.1929	β^+	0.24	121 Ag 47	8.3835	β^-	-0.11
				121 Cd 48	8.4300	β^-	1.13
118 Rh 45	8.3301	?		121 In 49	8.4639	β^-	1.36
118 Pd 46	8.4065	β^-	0.28	121 Sn 50	8.4852	β^-	4.99
118 Ag 47	8.4347	β^-	0.58	121 Sb 51	8.4820		57.36%
118 Cd 48	8.4879	β^-	3.48	121 Te 52	8.4669	β^+	6.16
118 In 49	8.4857	β^-	0.70	121 I 53	8.4417	β^+	3.88
118 Sn 50	8.5165		24.23%	121 Xe 54	8.4044	β^+	3.38
118 Sb 51	8.4789	β^+	2.33	121 Cs 55	8.3533	β^+	2.19
118 Te 52	8.4699	EC	5.71	121 Ba 56	8.2905	β^+	1.47
118 I 53	8.4036	β^+	2.91	121 La 57	8.2185	β^+	0.72
118 Xe 54	8.3720	β^+	2.36	121 Ce 58	8.1300	?	
118 Cs 55	8.2866	β^+	1.15				
118 Ba 56	8.2255	β^+	0.74	122 Ag 47	8.3554	β^-	-0.32
118 La 57	8.1158	?		122 Cd 48	8.4240	β^-	0.72
				122 In 49	8.4421	β^-	0.18
119 Rh 45	8.3128	?		122 Sn 50	8.4879	$\beta\beta$	4.63%
119 Pd 46	8.3741	β^-	-0.04	122 Sb 51	8.4682	β^-	5.37
119 Ag 47	8.4225	β^-	0.32	122 Te 52	8.4780		2.60%
119 Cd 48	8.4608	β^-	2.21	122 I 53	8.4369	β^+	2.34
119 In 49	8.4862	β^-	2.16	122 Xe 54	8.4232	EC	4.86
119 Sn 50	8.4995		8.59%	122 Cs 55	8.3589	β^+	1.32
119 Sb 51	8.4879	EC	5.14	122 Ba 56	8.3210	β^+	2.07
119 Te 52	8.4620	β^+	4.76	122 La 57	8.2348	β^+	0.94
119 I 53	8.4259	β^+	3.06	122 Ce 58	8.1727	?	
119 Xe 54	8.3773	β^+	2.54				
119 Cs 55	8.3176	β^+	1.63	123 Ag 47	8.3411	β^-	-0.51
119 Ba 56	8.2430	β^+	0.73	123 Cd 48	8.3946	β^-	0.32
119 La 57	8.1572	?		123 In 49	8.4379	β^-	0.78
				123 Sn 50	8.4673	β^-	7.05
120 Pd 46	8.3611	β^-	-0.30	123 Sb 51	8.4723		42.64%
120 Ag 47	8.3963	β^-	0.09	123 Te 52	8.4655	EC	0.91%
120 Cd 48	8.4582	β^-	1.71	123 I 53	8.4491	β^+	4.68
120 In 49	8.4663	β^-	0.49	123 Xe 54	8.4210	β^+	3.87
120 Sn 50	8.5045		32.59%	123 Cs 55	8.3805	β^+	2.55

A X Z	B/A (MeV)	$\rightarrow$	$\log t_{1/2}$ or %	A X Z	B/A (MeV)	$\rightarrow$	$\log t_{1/2}$ or %
123 Ba 56	8.3297	β^+	2.21	127 Cd 48	8.3152	β^-	-0.43
123 La 57	8.2674	β^+	1.23	127 In 49	8.3757	β^-	0.04
123 Ce 58	8.1908	β^+	0.51	127 Sn 50	8.4209	β^-	3.88
				127 Sb 51	8.4399	β^-	5.52
124 Ag 47	8.3117	β^-	-0.76	127 Te 52	8.4462	β^-	4.53
124 Cd 48	8.3871	β^-	0.10	127 I 53	8.4455		100.00%
124 In 49	8.4144	β^-	0.49	127 Xe 54	8.4341	EC	6.50
124 Sn 50	8.4674	$\beta\beta$	5.79%	127 Cs 55	8.4116	β^+	4.35
124 Sb 51	8.4561	β^-	6.72	127 Ba 56	8.3783	β^+	2.88
124 Te 52	8.4733		4.82%	127 La 57	8.3351	β^+	2.49
124 I 53	8.4415	β^+	5.56	127 Ce 58	8.2806	β^+	1.49
124 Xe 54	8.4375	$\beta\beta$	0.10%	127 Pr 59	8.2152	β^+	0.62
124 Cs 55	8.3835	β^+	1.49	127 Nd 60	8.1381	β^+	0.26
124 Ba 56	8.3559	β^+	2.82				
124 La 57	8.2786	β^+	1.46	128 Cd 48	8.3036	β^-	-0.47
124 Ce 58	8.2273	β^+	0.78	128 In 49	8.3528	β^-	-0.08
124 Pr 59	8.1267	β^+	0.08	128 Sn 50	8.4168	β^-	3.55
				128 Sb 51	8.4206	β^-	4.51
125 Cd 48	8.3575	β^-	-0.19	128 Te 52	8.4488	$\beta\beta$	31.69%
125 In 49	8.4085	β^-	0.37	128 I 53	8.4329	β^-	3.18
125 Sn 50	8.4456	β^-	5.92	128 Xe 54	8.4433		1.91%
125 Sb 51	8.4582	β^-	7.94	128 Cs 55	8.4065	β^+	2.34
125 Te 52	8.4581		7.14%	128 Ba 56	8.3963	EC	5.32
125 I 53	8.4503	EC	6.71	128 La 57	8.3382	β^+	2.48
125 Xe 54	8.4309	β^+	4.78	128 Ce 58	8.3072	β^+	0.61
125 Cs 55	8.3999	β^+	3.43	128 Pr 59	8.2289	β^+	0.49
125 Ba 56	8.3571	β^+	2.32	128 Nd 60	8.1748	β^+	0.60
125 La 57	8.3057	β^+	1.88				
125 Ce 58	8.2408	β^+	0.95	129 In 49	8.3398	β^-	-0.21
125 Pr 59	8.1645	β^+	0.52	129 Sn 50	8.3931	β^-	2.13
				129 Sb 51	8.4180	β^-	4.20
126 Cd 48	8.3473	β^-	-0.30	129 Te 52	8.4304	β^-	3.62
126 In 49	8.3846	β^-	0.20	129 I 53	8.4360	β^-	14.69
126 Sn 50	8.4436	β^-	12.50	129 Xe 54	8.4314		26.40%
126 Sb 51	8.4404	β^-	6.03	129 Cs 55	8.4161	β^+	5.06
126 Te 52	8.4633		18.95%	129 Ba 56	8.3911	β^+	3.90
126 I 53	8.4400	β^+	6.05	129 La 57	8.3562	β^+	2.84
126 Xe 54	8.4438	$\beta\beta$	0.09%	129 Ce 58	8.3068	β^+	2.32
126 Cs 55	8.3992	β^+	1.99	129 Pr 59	8.2561	β^+	1.48
126 Ba 56	8.3798	β^+	3.78	129 Nd 60	8.1894	β^+	0.85
126 La 57	8.3135	β^+	1.73				
126 Ce 58	8.2723	β^+	1.70	130 In 49	8.3148	β^-	-0.49
126 Pr 59	8.1832	β^+	0.50	130 Sn 50	8.3877	β^-	2.35
				130 Sb 51	8.3982	β^-	3.37

A X Z	B/A (MeV)	$\rightarrow$	$\log t_{1/2}$ or %	A X Z	B/A (MeV)	$\rightarrow$	$\log t_{1/2}$ or %
130 Te 52	8.4303	$\beta\beta$	33.80%	133 Cs 55	8.4100		100.00%
130 I 53	8.4211	β^-	4.65	133 Ba 56	8.4002	EC	8.52
130 Xe 54	8.4377		4.10%	133 La 57	8.3776	β^+	4.15
130 Cs 55	8.4088	β^+	3.24	133 Ce 58	8.3496	β^+	3.76
130 Ba 56	8.4056	$\beta\beta$	0.11%	133 Pr 59	8.3112	β^+	2.59
130 La 57	8.3565	β^+	2.72	133 Nd 60	8.2632	β^+	1.85
130 Ce 58	8.3335	β^+	3.18	133 Pm 61	8.2047	β^+	
130 Pr 59	8.2653	β^+	1.60	133 Sm 62	8.1357	β^+	0.57
130 Nd 60	8.2206	β^+	1.45				
130 Pm 61	8.1309	β^+	0.34	134 Sn 50	8.2811	β^-	0.05
				134 Sb 51	8.3256	β^-	-0.11
131 In 49	8.2993	β^-	-0.55	134 Te 52	8.3826	β^-	3.40
131 Sn 50	8.3634	β^-	1.75	134 I 53	8.3884	β^-	3.50
131 Sb 51	8.3929	β^-	3.14	134 Xe 54	8.4137	$\beta\beta$	10.40%
131 Te 52	8.4112	β^-	3.18	134 Cs 55	8.3987	β^-	7.81
131 I 53	8.4223	β^-	5.84	134 Ba 56	8.4082		2.42%
131 Xe 54	8.4237		21.20%	134 La 57	8.3747	β^+	2.59
131 Cs 55	8.4151	EC	5.92	134 Ce 58	8.3651	EC	5.44
131 Ba 56	8.3987	β^+	6.00	134 Pr 59	8.3129	β^+	3.01
131 La 57	8.3701	β^+	3.55	134 Nd 60	8.2864	β^+	2.71
131 Ce 58	8.3334	β^+	2.79	134 Pm 61	8.2143	β^+	0.70
131 Pr 59	8.2874	β^+	1.96	134 Sm 62	8.1680	β^+	1.00
131 Nd 60	8.2313	β^+	1.43				
131 Pm 61	8.1635	?		135 Sb 51	8.2921	β^-	0.23
				135 Te 52	8.3465	β^-	1.28
132 In 49	8.2583	β^-	-0.70	135 I 53	8.3848	β^-	4.37
132 Sn 50	8.3554	β^-	1.60	135 Xe 54	8.3986	β^-	4.52
132 Sb 51	8.3745	β^-	2.22	135 Cs 55	8.4014	β^-	13.86
132 Te 52	8.4086	β^-	5.44	135 Ba 56	8.3976		6.59%
132 I 53	8.4065	β^-	3.92	135 La 57	8.3829	β^+	4.85
132 Xe 54	8.4276		26.90%	135 Ce 58	8.3621	β^+	4.80
132 Cs 55	8.4056	β^+	5.75	135 Pr 59	8.3287	β^+	3.16
132 Ba 56	8.4094	$\beta\beta$	0.10%	135 Nd 60	8.2877	β^+	2.87
132 La 57	8.3678	β^+	4.24	135 Pm 61	8.2374	β^+	1.65
132 Ce 58	8.3522	β^+	4.10	135 Sm 62	8.1788	β^+	1.01
132 Pr 59	8.2924	β^+	1.98	135 Eu 63	8.1084	β^+	0.18
132 Nd 60	8.2582	β^+	2.02				
132 Pm 61	8.1773	β^+	0.80	136 Sb 51	8.2565	β^-	-0.09
				136 Te 52	8.3194	β^-	1.24
133 Sn 50	8.3120	β^-	0.16	136 I 53	8.3510	β^-	1.92
133 Sb 51	8.3650	β^-	2.18	136 Xe 54	8.3962	$\beta\beta$	8.90%
133 Te 52	8.3892	β^-	2.88	136 Cs 55	8.3898	β^-	6.06
133 I 53	8.4053	β^-	4.87	136 Ba 56	8.4028		7.85%
133 Xe 54	8.4127	β^-	5.66	136 La 57	8.3759	β^+	2.77

A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %	A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %
136 Ce 58	8.3737	$\beta\beta$	0.19%	139 Sm 62	8.2408	β^+	2.19
136 Pr 59	8.3302	β^+	2.90	139 Eu 63	8.1871	β^+	1.25
136 Nd 60	8.3082	β^+	3.48	139 Gd 64	8.1261	β^+	0.69
136 Pm 61	8.2447	β^+	1.67	139 Tb 65	8.0537	?	
136 Sm 62	8.2058	β^+	1.67				
136 Eu 63	8.1233	β^+	0.52	140 I 53	8.2340	β^-	-0.07
				140 Xe 54	8.2910	β^-	1.13
137 Te 52	8.2821	β^-	0.40	140 Cs 55	8.3144	β^-	1.80
137 I 53	8.3271	β^-	1.39	140 Ba 56	8.3532	β^-	6.04
137 Xe 54	8.3643	β^-	2.36	140 La 57	8.3551	β^-	5.16
137 Cs 55	8.3890	β^-	8.98	140 Ce 58	8.3764		88.48%
137 Ba 56	8.3919		11.23%	140 Pr 59	8.3466	β^+	2.31
137 La 57	8.3818	EC	12.28	140 Nd 60	8.3394	EC	5.46
137 Ce 58	8.3671	β^+	4.51	140 Pm 61	8.2904	β^+	0.96
137 Pr 59	8.3417	β^+	3.66	140 Sm 62	8.2605	β^+	2.95
137 Nd 60	8.3091	β^+	3.36	140 Eu 63	8.1949	β^+	0.18
137 Pm 61	8.2626	β^+	2.16	140 Gd 64	8.1550	β^+	1.20
137 Sm 62	8.2127	β^+	1.65	140 Tb 65	8.0687	β^+	0.38
137 Eu 63	8.1521	β^+	1.04				
137 Gd 64	8.0822	β^+	0.85	141 I 53	8.2062	β^-	-0.37
				141 Xe 54	8.2562	β^-	0.24
138 Te 52	8.2543	β^-	0.15	141 Cs 55	8.2943	β^-	1.40
138 I 53	8.2948	β^-	0.81	141 Ba 56	8.3260	β^-	3.04
138 Xe 54	8.3458	β^-	2.93	141 La 57	8.3433	β^-	4.15
138 Cs 55	8.3602	β^-	3.30	141 Ce 58	8.3555	β^-	6.45
138 Ba 56	8.3935		71.70%	141 Pr 59	8.3541		100.00%
138 La 57	8.3752	β^+	0.09%	141 Nd 60	8.3356	β^+	3.95
138 Ce 58	8.3771	$\beta\beta$	0.25%	141 Pm 61	8.3037	β^+	3.10
138 Pr 59	8.3393	β^+	1.94	141 Sm 62	8.2659	β^+	2.79
138 Nd 60	8.3256	β^+	4.26	141 Eu 63	8.2210	β^+	1.61
138 Pm 61	8.2700	β^+	1.00	141 Gd 64	8.1641	β^+	1.15
138 Sm 62	8.2359	β^+	2.27	141 Tb 65	8.0994	β^+	0.54
138 Eu 63	8.1634	β^+	1.08	141 Dy 66	8.0276	β^+	-0.05
138 Gd 64	8.1137	?					
				142 Xe 54	8.2349	β^-	0.09
139 I 53	8.2683	β^-	0.36	142 Cs 55	8.2649	β^-	0.23
139 Xe 54	8.3116	β^-	1.60	142 Ba 56	8.3109	β^-	2.80
139 Cs 55	8.3424	β^-	2.75	142 La 57	8.3209	β^-	3.74
139 Ba 56	8.3671	β^-	3.70	142 Ce 58	8.3471	$\beta\beta$	11.08%
139 La 57	8.3781		99.91%	142 Pr 59	8.3364	β^-	4.84
139 Ce 58	8.3705	EC	7.08	142 Nd 60	8.3461		27.13%
139 Pr 59	8.3495	β^+	4.20	142 Pm 61	8.3063	β^+	1.61
139 Nd 60	8.3238	β^+	3.25	142 Sm 62	8.2860	β^+	3.64
139 Pm 61	8.2857	β^+	2.40	142 Eu 63	8.2286	β^+	0.37

A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %	A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %
142 Gd 64	8.1936	β^+	1.85	145 Tb 65	8.1788	?	
142 Tb 65	8.1148	β^+	-0.22	145 Dy 66	8.1231	β^+	1.00
142 Dy 66	8.0593	β^+	0.36	145 Ho 67	8.0520	β^+	0.38
				145 Er 68	7.9752	β^+	-0.05
143 Xe 54	8.1983	β^-	-0.52				
143 Cs 55	8.2439	β^-	0.25	146 Cs 55	8.1579	β^-	-0.49
143 Ba 56	8.2821	β^-	1.16	146 Ba 56	8.2167	β^-	0.35
143 La 57	8.3063	β^-	2.93	146 La 57	8.2396	β^-	0.80
143 Ce 58	8.3247	β^-	5.08	146 Ce 58	8.2790	β^-	2.91
143 Pr 59	8.3295	β^-	6.07	146 Pr 59	8.2808	β^-	3.16
143 Nd 60	8.3306		12.18%	146 Nd 60	8.3042	$\beta\beta$	17.19%
143 Pm 61	8.3178	β^+	7.36	146 Pm 61	8.2887	β^+	8.24
143 Sm 62	8.2883	β^+	2.72	146 Sm 62	8.2939	α	15.51
143 Eu 63	8.2466	β^+	2.20	146 Eu 63	8.2620	β^+	5.60
143 Gd 64	8.1992	β^+	1.59	146 Gd 64	8.2496	β^+	6.62
143 Tb 65	8.1420	β^+	1.08	146 Tb 65	8.1889	β^+	0.90
143 Dy 66	8.0752	β^+	0.61	146 Dy 66	8.1482	β^+	1.46
143 Ho 67	7.9996	?		146 Ho 67	8.0697	β^+	0.56
				146 Er 68	8.0135	β^+	0.23
144 Xe 54	8.1755	β^-	0.06	146 Tm 69	7.9128	β^+	-0.63
144 Cs 55	8.2122	β^-	0.00				
144 Ba 56	8.2655	β^-	1.06	147 Cs 55	8.1339	β^-	-0.65
144 La 57	8.2818	β^-	1.61	147 Ba 56	8.1915	β^-	-0.05
144 Ce 58	8.3148	β^-	7.39	147 La 57	8.2253	β^-	0.60
144 Pr 59	8.3116	β^-	3.02	147 Ce 58	8.2537	β^-	1.75
144 Nd 60	8.3270		23.80%	147 Pr 59	8.2707	β^-	2.91
144 Pm 61	8.3054	β^+	7.50	147 Nd 60	8.2837	β^-	5.98
144 Sm 62	8.3037	$\beta\beta$	3.10%	147 Pm 61	8.2844	β^-	7.92
144 Eu 63	8.2544	β^+	1.01	147 Sm 62	8.2806		15.00%
144 Gd 64	8.2191	β^+	2.43	147 Eu 63	8.2636	β^+	6.32
144 Tb 65	8.1556	β^+	0.00	147 Gd 64	8.2434	β^+	5.14
144 Dy 66	8.1069	β^+	0.96	147 Tb 65	8.2067	β^+	3.79
144 Ho 67	8.0198	β^+	-0.15	147 Dy 66	8.1580	β^+	1.60
				147 Ho 67	8.0973	β^+	0.76
145 Cs 55	8.1895	β^-	-0.23	147 Er 68	8.0301	β^+	0.40
145 Ba 56	8.2385	β^-	0.63	147 Tm 69	7.9518	β^+	-0.25
145 La 57	8.2671	β^-	1.39				
145 Ce 58	8.2901	β^-	2.26	148 Cs 55	8.1017	β^-	-0.80
145 Pr 59	8.3022	β^-	4.33	148 Ba 56	8.1675	β^-	-0.22
145 Nd 60	8.3093		8.30%	148 La 57	8.1968	β^-	0.02
145 Pm 61	8.3027	EC	8.75	148 Ce 58	8.2406	β^-	1.75
145 Sm 62	8.2931	EC	7.47	148 Pr 59	8.2492	β^-	2.13
145 Eu 63	8.2693	β^+	5.71	148 Nd 60	8.2772	$\beta\beta$	5.76%
145 Gd 64	8.2291	β^+	3.14	148 Pm 61	8.2683	β^-	5.67

A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %	A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %
148 Sm 62	8.2797		11.30%	151 La 57	8.1379	?	
148 Eu 63	8.2534	β^+	6.67	151 Ce 58	8.1778	β^-	0.01
148 Gd 64	8.2484	α	9.37	151 Pr 59	8.2079	β^-	1.28
148 Tb 65	8.2047	β^+	3.56	151 Nd 60	8.2304	β^-	2.87
148 Dy 66	8.1813	β^+	2.27	151 Pm 61	8.2414	β^-	5.01
148 Ho 67	8.1125	β^+	0.34	151 Sm 62	8.2440	β^-	9.45
148 Er 68	8.0616	β^+	0.66	151 Eu 63	8.2394		47.80%
148 Tm 69	7.9752	β^+	-0.15	151 Gd 64	8.2311	EC	7.03
148 Yb 70	7.9074	?		151 Tb 65	8.2089	β^+	4.80
				151 Dy 66	8.1847	β^+	3.03
149 Cs 55	8.0792	?		151 Ho 67	8.1456	β^+	1.55
149 Ba 56	8.1394	β^-	-0.46	151 Er 68	8.1059	β^+	1.37
149 La 57	8.1834	β^-	0.02	151 Tm 69	8.0508	β^+	0.62
149 Ce 58	8.2151	β^-	0.72	151 Yb 70	7.9892	β^+	0.20
149 Pr 59	8.2380	β^-	2.13	151 Lu 71	7.9067	p	-1.06
149 Nd 60	8.2555	β^-	3.79				
149 Pm 61	8.2616	β^-	5.28	152 Ce 58	8.1613	β^-	0.15
149 Sm 62	8.2635		13.80%	152 Pr 59	8.1852	β^-	0.56
149 Eu 63	8.2536	EC	6.91	152 Nd 60	8.2241	β^-	2.84
149 Gd 64	8.2395	β^+	5.90	152 Pm 61	8.2262	β^-	2.39
149 Tb 65	8.2099	β^+	4.17	152 Sm 62	8.2441		26.70%
149 Dy 66	8.1791	β^+	2.40	152 Eu 63	8.2267	β^+	8.63
149 Ho 67	8.1334	β^+	1.32	152 Gd 64	8.2335	$\beta\beta$	0.20%
149 Er 68	8.0736	β^+	0.60	152 Tb 65	8.2021	β^+	4.80
149 Tm 69	8.0068	β^+	-0.05	152 Dy 66	8.1930	EC	3.93
149 Yb 70	7.9298	?		152 Ho 67	8.1452	β^+	2.21
				152 Er 68	8.1197	α	1.01
150 Ba 56	8.1173	β^-	-0.52	152 Tm 69	8.0575	β^+	0.90
150 La 57	8.1551	β^-	-0.07	152 Yb 70	8.0164	β^+	0.48
150 Ce 58	8.2021	β^-	0.60	152 Lu 71	7.9301	β^+	-0.15
150 Pr 59	8.2170	β^-	0.79				
150 Nd 60	8.2497	$\beta\beta$	5.64%	153 Ce 58	8.1342	?	
150 Pm 61	8.2439	β^-	3.98	153 Pr 59	8.1719	β^-	0.63
150 Sm 62	8.2617		7.40%	153 Nd 60	8.2029	β^-	1.50
150 Eu 63	8.2414	β^+	9.06	153 Pm 61	8.2213	β^-	2.50
150 Gd 64	8.2427	α	13.75	153 Sm 62	8.2286	β^-	5.22
150 Tb 65	8.2064	β^+	4.10	153 Eu 63	8.2288		52.20%
150 Dy 66	8.1892	β^+	2.63	153 Gd 64	8.2205	EC	7.32
150 Ho 67	8.1403	β^+	1.86	153 Tb 65	8.2051	β^+	5.31
150 Er 68	8.1077	β^+	1.27	153 Dy 66	8.1858	β^+	4.36
150 Tm 69	8.0257	β^+	0.34	153 Ho 67	8.1537	β^+	2.08
150 Yb 70	7.9663	?		153 Er 68	8.1188	α	1.57
150 Lu 71	7.8685	p	-1.46	153 Tm 69	8.0714	α	0.17
				153 Yb 70	8.0226	α	0.62

A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %	A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %
153 Lu 71	7.9598	α	-0.05	156 Hf 72	7.9536	α	-1.60
				156 Ta 73	7.8743	p	-0.84
154 Pr 59	8.1462	β^-	0.36				
154 Nd 60	8.1926	β^-	1.41	157 Nd 60	8.1294	?	
154 Pm 61	8.2057	β^-	2.02	157 Pm 61	8.1637	β^-	1.03
154 Sm 62	8.2269	ββ	22.70%	157 Sm 62	8.1877	β^-	2.68
154 Eu 63	8.2172	β^-	8.43	157 Eu 63	8.1999	β^-	4.74
154 Gd 64	8.2249		2.18%	157 Gd 64	8.2036		15.65%
154 Tb 65	8.1967	β^+	4.89	157 Tb 65	8.1982	EC	9.35
154 Dy 66	8.1932	α	13.98	157 Dy 66	8.1847	β^+	4.47
154 Ho 67	8.1507	β^+	2.85	157 Ho 67	8.1635	β^+	2.88
154 Er 68	8.1325	β^+	2.35	157 Er 68	8.1364	β^+	3.05
154 Tm 69	8.0795	β^+	0.91	157 Tm 69	8.1029	β^+	2.34
154 Yb 70	8.0453	α	-0.39	157 Yb 70	8.0627	β^+	1.59
154 Lu 71	7.9701	?		157 Lu 71	8.0136	α	0.83
154 Hf 72	7.9218	β^+	0.30	157 Hf 72	7.9610	α	-0.96
				157 Ta 73	7.8966	α	-2.00
155 Pr 59	8.1306	?					
155 Nd 60	8.1685	β^-	0.95	158 Pm 61	8.1425	β^-	0.68
155 Pm 61	8.1959	β^-	1.62	158 Sm 62	8.1774	β^-	2.50
155 Sm 62	8.2113	β^-	3.13	158 Eu 63	8.1848	β^-	3.44
155 Eu 63	8.2167	β^-	8.18	158 Gd 64	8.2019		24.84%
155 Gd 64	8.2133		14.80%	158 Tb 65	8.1892	β^+	9.75
155 Tb 65	8.2030	EC	5.66	158 Dy 66	8.1902	ββ	0.10%
155 Dy 66	8.1844	β^+	4.55	158 Ho 67	8.1584	β^+	2.83
155 Ho 67	8.1594	β^+	3.46	158 Er 68	8.1422	β^+	3.92
155 Er 68	8.1295	β^+	2.50	158 Tm 69	8.0959	β^+	2.38
155 Tm 69	8.0885	β^+	1.33	158 Yb 70	8.0793	β^+	1.95
155 Yb 70	8.0448	α	0.26	158 Lu 71	8.0237	β^+	1.03
155 Lu 71	7.9884	α	-0.85	158 Hf 72	7.9865	β^+	0.45
155 Hf 72	7.9317	β^+	-0.05	158 Ta 73	7.9081	α	-1.44
				158 W 74	7.8586	α	-3.05
156 Nd 60	8.1557	β^-	0.74				
156 Pm 61	8.1770	β^-	1.43	159 Pm 61	8.1268	?	
156 Sm 62	8.2051	β^-	4.53	159 Sm 62	8.1576	β^-	1.06
156 Eu 63	8.2047	β^-	6.12	159 Eu 63	8.1768	β^-	3.04
156 Gd 64	8.2154		20.47%	159 Gd 64	8.1877	β^-	4.82
156 Tb 65	8.1947	β^+	5.66	159 Tb 65	8.1889		100.00%
156 Dy 66	8.1925	ββ	0.06%	159 Dy 66	8.1816	EC	7.10
156 Ho 67	8.1593	β^+	3.53	159 Ho 67	8.1652	β^+	3.30
156 Er 68	8.1435	β^+	3.07	159 Er 68	8.1428	β^+	3.33
156 Tm 69	8.0899	β^+	1.92	159 Tm 69	8.1137	β^+	2.74
156 Yb 70	8.0620	β^+	1.42	159 Yb 70	8.0770	β^+	1.98
156 Lu 71	7.9964	α	-0.70	159 Lu 71	8.0344	β^+	1.08

A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %	A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %
159 Hf 72	7.9875	β^+	0.75	162 Ta 73	7.9694	β^+	0.55
159 Ta 73	7.9292	α	-0.24	162 W 74	7.9289	β^+	0.14
159 W 74	7.8696	α	-2.14	162 Re 75	7.8488	α	-0.97
				162 Os 76	7.7973	α	-2.72
160 Sm 62	8.1449	β^-	0.98				
160 Eu 63	8.1623	β^-	1.58	163 Eu 63	8.1158	?	
160 Gd 64	8.1831	ββ	21.86%	163 Gd 64	8.1414	β^-	1.83
160 Tb 65	8.1775	β^-	6.80	163 Tb 65	8.1557	β^-	3.07
160 Dy 66	8.1841		2.34%	163 Dy 66	8.1618		24.90%
160 Ho 67	8.1587	β^+	3.19	163 Ho 67	8.1570	EC	11.16
160 Er 68	8.1517	EC	5.01	163 Er 68	8.1448	β^+	3.65
160 Tm 69	8.1100	β^+	2.75	163 Tm 69	8.1250	β^+	3.81
160 Yb 70	8.0926	β^+	2.46	163 Yb 70	8.0996	β^+	2.82
160 Lu 71	8.0421	β^+	1.56	163 Lu 71	8.0665	β^+	2.38
160 Hf 72	8.0067	β^+	1.13	163 Hf 72	8.0283	β^+	1.60
160 Ta 73	7.9387	β^+	0.19	163 Ta 73	7.9817	β^+	1.03
160 W 74	7.8936	α	-1.04	163 W 74	7.9312	β^+	0.44
160 Re 75	7.8124	p	-3.10	163 Re 75	7.8710	α	-0.59
				163 Os 76	7.8091	α	
161 Sm 62	8.1229	?					
161 Eu 63	8.1489	β^-	1.41	164 Gd 64	8.1303	β^-	1.65
161 Gd 64	8.1673	β^-	2.34	164 Tb 65	8.1398	β^-	2.26
161 Tb 65	8.1745	β^-	5.77	164 Dy 66	8.1588		28.20%
161 Dy 66	8.1734		18.90%	164 Ho 67	8.1480	EC	3.24
161 Ho 67	8.1632	EC	3.95	164 Er 68	8.1491	ββ	1.61%
161 Er 68	8.1459	β^+	4.06	164 Tm 69	8.1202	β^+	2.08
161 Tm 69	8.1214	β^+	3.30	164 Yb 70	8.1093	EC	3.66
161 Yb 70	8.0926	β^+	2.40	164 Lu 71	8.0664	β^+	2.27
161 Lu 71	8.0548	β^+	1.89	164 Hf 72	8.0435	β^+	2.05
161 Hf 72	8.0088	β^+	1.23	164 Ta 73	7.9868	β^+	1.15
161 Ta 73	7.9574	β^+	0.43	164 W 74	7.9517	β^+	0.78
161 W 74	7.9021	α	-0.39	164 Re 75	7.8815	β^+	-0.42
161 Re 75	7.8361	p	-3.43	164 Os 76	7.8341	α	-1.68
162 Eu 63	8.1291	β^-	1.03	165 Gd 64	8.1101	?	
162 Gd 64	8.1591	β^-	2.70	165 Tb 65	8.1308	β^-	2.10
162 Tb 65	8.1629	β^-	2.66	165 Dy 66	8.1440	β^-	3.92
162 Dy 66	8.1735		25.50%	165 Ho 67	8.1470		100.00%
162 Ho 67	8.1555	β^+	2.95	165 Er 68	8.1400	EC	4.57
162 Er 68	8.1525	ββ	0.14%	165 Tm 69	8.1256	β^+	5.03
162 Tm 69	8.1180	β^+	3.11	165 Yb 70	8.1041	β^+	2.77
162 Yb 70	8.1027	β^+	3.05	165 Lu 71	8.0756	β^+	2.81
162 Lu 71	8.0551	β^+	1.91	165 Hf 72	8.0430	β^+	1.88
162 Hf 72	8.0272	β^+	1.58	165 Ta 73	8.0028	β^+	1.49

A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %	A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %
165 W 74	7.9557	β^+	0.71	168 Pt 78	7.7744	α	-2.70
165 Re 75	7.9017	β^+	0.38				
165 Os 76	7.8438	α	-1.15	169 Dy 66	8.0948	β^-	1.59
				169 Ho 67	8.1091	β^-	2.45
166 Tb 65	8.1126	?		169 Er 68	8.1171	β^-	5.91
166 Dy 66	8.1373	β^-	5.47	169 Tm 69	8.1145		100.00%
166 Ho 67	8.1356	β^-	4.98	169 Yb 70	8.1045	EC	6.44
166 Er 68	8.1420		33.60%	169 Lu 71	8.0863	β^+	5.09
166 Tm 69	8.1190	β^+	4.44	169 Hf 72	8.0623	β^+	2.29
166 Yb 70	8.1124	EC	5.31	169 Ta 73	8.0315	β^+	2.47
166 Lu 71	8.0747	β^+	2.20	169 W 74	7.9947	β^+	1.88
166 Hf 72	8.0560	β^+	2.61	169 Re 75	7.9510	?	
166 Ta 73	8.0052	β^+	1.54	169 Os 76	7.9010	β^+	0.53
166 W 74	7.9750	β^+	1.27	169 Ir 77	7.8450	α	-0.40
166 Re 75	7.9138	α	0.45	169 Pt 78	7.7851	α	-2.30
166 Os 76	7.8714	α	-0.74				
166 Ir 77	7.7898	α	-1.98	170 Ho 67	8.0939	β^-	2.22
				170 Er 68	8.1120	$\beta\beta$	14.90%
167 Tb 65	8.1012	?		170 Tm 69	8.1056	EC	7.05
167 Dy 66	8.1211	β^-	2.57	170 Yb 70	8.1067		3.05%
167 Ho 67	8.1305	β^-	4.05	170 Lu 71	8.0817	β^+	5.24
167 Er 68	8.1318		22.95%	170 Hf 72	8.0707	β^+	4.76
167 Tm 69	8.1226	EC	5.90	170 Ta 73	8.0308	β^+	2.61
167 Yb 70	8.1062	β^+	3.02	170 W 74	8.0131	β^+	2.16
167 Lu 71	8.0828	β^+	3.49	170 Re 75	7.9554	β^+	0.96
167 Hf 72	8.0542	β^+	2.09	170 Os 76	7.9212	β^+	0.86
167 Ta 73	8.0158	β^+	1.92	170 Ir 77	7.8578	α	0.02
167 W 74	7.9775	β^+	1.30	170 Pt 78	7.8132	α	-2.22
167 Re 75	7.9286	β^+	0.79				
167 Os 76	7.8749	α	-0.08	171 Ho 67	8.0837	β^-	1.72
167 Ir 77	7.8127	α	-2.30	171 Er 68	8.0978	β^-	4.43
				171 Tm 69	8.1019	β^-	7.78
168 Dy 66	8.1120	β^-	2.72	171 Yb 70	8.0979		14.30%
168 Ho 67	8.1170	β^-	2.25	171 Lu 71	8.0847	β^+	5.85
168 Er 68	8.1296		26.80%	171 Hf 72	8.0661	β^+	4.64
168 Tm 69	8.1150	β^+	6.91	171 Ta 73	8.0399	β^+	3.15
168 Yb 70	8.1119	$\beta\beta$	0.13%	171 W 74	8.0086	β^+	2.16
168 Lu 71	8.0806	β^+	2.52	171 Re 75	7.9708	β^+	1.18
168 Hf 72	8.0652	β^+	3.19	171 Os 76	7.9249	β^+	0.90
168 Ta 73	8.0209	β^+	2.08	171 Ir 77	7.8726	α	0.18
168 W 74	7.9936	β^+	1.72	171 Pt 78	7.8175	α	-1.60
168 Re 75	7.9349	β^+	0.64				
168 Os 76	7.8962	β^+	0.32	172 Er 68	8.0905	β^-	5.25
168 Ir 77	7.8241	α	-0.79	172 Tm 69	8.0911	β^-	5.36

A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %	A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %
172 Yb 70	8.0975		21.90%	175 Re 75	7.9948	β^+	2.55
172 Lu 71	8.0783	β^+	5.76	175 Os 76	7.9603	β^+	1.92
172 Hf 72	8.0717	EC	7.77	175 Ir 77	7.9182	β^+	0.95
172 Ta 73	8.0385	β^+	3.34	175 Pt 78	7.8702	α	0.40
172 W 74	8.0195	β^+	2.60	175 Au 79	7.8156	α	-0.70
172 Re 75	7.9723	β^+	1.18	175 Hg 80	7.7603	α	-1.70
172 Os 76	7.9418	β^+	1.28				
172 Ir 77	7.8801	β^+	0.64	176 Tm 69	8.0447	β^-	2.06
172 Pt 78	7.8395	α	-1.02	176 Yb 70	8.0641	$\beta\beta$	12.70%
172 Au 79	7.7654	α	-2.20	176 Lu 71	8.0591		2.59%
				176 Hf 72	8.0614		5.21%
173 Er 68	8.0740	β^-	1.92	176 Ta 73	8.0393	β^+	4.46
173 Tm 69	8.0845	β^-	4.47	176 W 74	8.0303	EC	3.95
173 Yb 70	8.0875		16.12%	176 Re 75	7.9943	β^+	2.50
173 Lu 71	8.0791	EC	7.64	176 Os 76	7.9718	β^+	2.33
173 Hf 72	8.0653	β^+	4.93	176 Ir 77	7.9221	β^+	0.90
173 Ta 73	8.0395	β^+	4.05	176 Pt 78	7.8887	β^+	0.80
173 W 74	8.0119	β^+	2.66	176 Au 79	7.8246	α	0.03
173 Re 75	7.9849	β^+	2.08	176 Hg 80	7.7827	α	-1.74
173 Os 76	7.9441	β^+	1.20	176 Tl 81	7.7076	?	
173 Ir 77	7.8970	β^+	0.95				
173 Pt 78	7.8451	α	-0.47	177 Tm 69	8.0364	β^-	1.93
173 Au 79	7.7873	α	-1.23	177 Yb 70	8.0500	β^-	3.84
				177 Lu 71	8.0535	β^-	5.76
174 Er 68	8.0651	β^-	2.30	177 Hf 72	8.0519		18.61%
174 Tm 69	8.0707	β^-	2.51	177 Ta 73	8.0409	β^+	5.31
174 Yb 70	8.0839		31.80%	177 W 74	8.0252	β^+	3.91
174 Lu 71	8.0715	β^+	8.02	177 Re 75	8.0015	β^+	2.92
174 Hf 72	8.0686	$\beta\beta$	0.16%	177 Os 76	7.9718	β^+	2.23
174 Ta 73	8.0420	β^+	3.58	177 Ir 77	7.9353	β^+	1.48
174 W 74	8.0268	β^+	3.27	177 Pt 78	7.8926	β^+	1.04
174 Re 75	7.9904	β^+	2.16	177 Au 79	7.8421	α	0.07
174 Os 76	7.9635	β^+	1.64	177 Hg 80	7.7896	α	-0.89
174 Ir 77	7.9028	β^+	0.95	177 Tl 81	7.7297	?	
174 Pt 78	7.8662	α	-0.05				
174 Au 79	7.8008	α	-0.92	178 Yb 70	8.0429	β^-	3.65
174 Hg 80	7.7547	?		178 Lu 71	8.0421	β^-	3.23
				178 Hf 72	8.0495		27.30%
175 Tm 69	8.0618	β^-	2.96	178 Ta 73	8.0344	β^+	2.75
175 Yb 70	8.0710	β^-	5.56	178 W 74	8.0295	EC	6.27
175 Lu 71	8.0692		97.41%	178 Re 75	7.9989	β^+	2.90
175 Hf 72	8.0608	EC	6.78	178 Os 76	7.9814	β^+	2.48
175 Ta 73	8.0449	β^+	4.58	178 Ir 77	7.9418	β^+	1.08
175 W 74	8.0238	β^+	3.32	178 Pt 78	7.9122	β^+	1.32

A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %	A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %
178 Au 79	7.8498	β^+	0.41				
178 Hg 80	7.8114	α	-0.58	182 Hf 72	8.0149	β^-	14.45
178 Tl 81	7.7441	?		182 Ta 73	8.0126	β^-	7.00
178 Pb 82	7.6954	?		182 W 74	8.0183		26.30%
				182 Re 75	7.9986	β^+	5.36
179 Yb 70	8.0263	β^-	2.68	182 Os 76	7.9893	EC	4.90
179 Lu 71	8.0351	β^-	4.22	182 Ir 77	7.9542	β^+	2.95
179 Hf 72	8.0386		13.63%	182 Pt 78	7.9343	β^+	2.26
179 Ta 73	8.0336	EC	7.76	182 Au 79	7.8923	β^+	1.19
179 W 74	8.0233	β^+	3.35	182 Hg 80	7.8608	β^+	1.03
179 Re 75	8.0038	β^+	3.07	182 Tl 81	7.7968	β^+	0.49
179 Os 76	7.9789	β^+	2.59	182 Pb 82	7.7563	α	-1.26
179 Ir 77	7.9474	β^+	1.90				
179 Pt 78	7.9110	β^+	1.33	183 Hf 72	8.0000	β^-	3.58
179 Au 79	7.8654	β^+	0.85	183 Ta 73	8.0068	β^-	5.64
179 Hg 80	7.8165	α	0.04	183 W 74	8.0083		14.30%
179 Tl 81	7.7607	α	-0.80	183 Re 75	8.0010	EC	6.78
179 Pb 82	7.7016	?		183 Os 76	7.9851	β^+	4.67
				183 Ir 77	7.9620	β^+	3.54
180 Lu 71	8.0221	β^-	2.53	183 Pt 78	7.9327	β^+	2.59
180 Hf 72	8.0350		35.10%	183 Au 79	7.8984	β^+	1.62
180 Ta 73	8.0259		0.01%	183 Hg 80	7.8597	β^+	0.97
180 W 74	8.0255	$\beta\beta$	0.13%	183 Tl 81	7.8136	?	
180 Re 75	8.0000	β^+	2.16	183 Pb 82	7.7618	α	-0.52
180 Os 76	7.9875	β^+	3.11				
180 Ir 77	7.9475	β^+	1.95	184 Hf 72	7.9907	β^-	4.17
180 Pt 78	7.9227	β^+	1.72	184 Ta 73	7.9938	β^-	4.50
180 Au 79	7.8708	β^+	0.91	184 W 74	8.0051		30.67%
180 Hg 80	7.8358	β^+	0.45	184 Re 75	7.9928	β^+	6.52
180 Tl 81	7.7700	β^+	-0.15	184 Os 76	7.9887	$\beta\beta$	0.02%
180 Pb 82	7.7256	?		184 Ir 77	7.9596	β^+	4.05
				184 Pt 78	7.9427	β^+	3.02
181 Lu 71	8.0126	β^-	2.32	184 Au 79	7.8997	β^+	1.72
181 Hf 72	8.0221	β^-	6.56	184 Hg 80	7.8734	β^+	1.49
181 Ta 73	8.0234		99.99%	184 Tl 81	7.8193	β^+	1.04
181 W 74	8.0181	EC	7.02	184 Pb 82	7.7824	α	-0.26
181 Re 75	8.0041	β^+	4.85				
181 Os 76	7.9836	β^+	3.80	185 Ta 73	7.9864	β^-	3.47
181 Ir 77	7.9568	β^+	2.47	185 W 74	7.9929	β^-	6.81
181 Pt 78	7.9236	β^+	1.71	185 Re 75	7.9910		37.40%
181 Au 79	7.8845	β^+	1.06	185 Os 76	7.9813	β^+	6.91
181 Hg 80	7.8398	β^+	0.56	185 Ir 77	7.9643	β^+	4.71
181 Tl 81	7.7886	?		185 Pt 78	7.9394	β^+	3.63
181 Pb 82	7.7331	α	-1.35	185 Au 79	7.9097	β^+	2.41

A X Z	B/A (MeV)	$\rightarrow$	$\log t_{1/2}$ or %	A X Z	B/A (MeV)	$\rightarrow$	$\log t_{1/2}$ or %
185 Hg 80	7.8740	β^+	1.69	189 Pt 78	7.9415	β^+	4.59
185 Tl 81	7.8340	β^+	1.29	189 Au 79	7.9206	β^+	3.24
185 Pb 82	7.7871	α	0.61	189 Hg 80	7.8943	β^+	2.66
185 Bi 83	7.7299	p	-4.36	189 Tl 81	7.8627	β^+	2.14
				189 Pb 82	7.8261	β^+	1.71
186 Ta 73	7.9719	β^-	2.80	189 Bi 83	7.7795	α	-0.17
186 W 74	7.9886	$\beta\beta$	28.60%				
186 Re 75	7.9813	EC	5.51	190 W 74	7.9471	β^-	3.26
186 Os 76	7.9828		1.58%	190 Re 75	7.9496	β^-	2.27
186 Ir 77	7.9580	β^+	4.78	190 Os 76	7.9621		26.40%
186 Pt 78	7.9464	β^+	3.90	190 Ir 77	7.9475	β^+	6.01
186 Au 79	7.9097	β^+	2.81	190 Pt 78	7.9466	$\beta\beta$	0.01%
186 Hg 80	7.8878	β^+	1.92	190 Au 79	7.9191	β^+	3.41
186 Tl 81	7.8431	β^+	1.44	190 Hg 80	7.9072	β^+	3.08
186 Pb 82	7.8091	α	0.68	190 Tl 81	7.8663	β^+	2.19
186 Bi 83	7.7398	α	-1.82	190 Pb 82	7.8407	β^+	1.86
				190 Bi 83	7.7907	α	0.80
187 Ta 73	7.9631	?		190 Po 84	7.7534	α	-2.70
187 W 74	7.9751	β^-	4.93				
187 Re 75	7.9780		62.60%	191 Re 75	7.9440	β^-	2.77
187 Os 76	7.9738		1.60%	191 Os 76	7.9506	β^-	6.12
187 Ir 77	7.9616	β^+	4.58	191 Ir 77	7.9481		37.30%
187 Pt 78	7.9408	β^+	3.93	191 Pt 78	7.9387	EC	5.38
187 Au 79	7.9173	β^+	2.70	191 Au 79	7.9250	β^+	4.06
187 Hg 80	7.8871	β^+	2.16	191 Hg 80	7.9043	β^+	3.47
187 Tl 81	7.8511	β^+	1.71	191 Tl 81	7.8748	?	
187 Pb 82	7.8087	β^+	1.26	191 Pb 82	7.8418	β^+	1.90
187 Bi 83	7.7567	α	-1.46	191 Bi 83	7.7994	α	1.08
				191 Po 84	7.7542	α	-1.81
188 W 74	7.9691	β^-	6.78				
188 Re 75	7.9668	β^-	4.79	192 Re 75	7.9309	β^-	1.20
188 Os 76	7.9739		13.30%	192 Os 76	7.9485	$\beta\beta$	41.00%
188 Ir 77	7.9548	β^+	5.17	192 Ir 77	7.9390	β^-	6.80
188 Pt 78	7.9479	EC	5.94	192 Pt 78	7.9425		0.79%
188 Au 79	7.9156	β^+	2.72	192 Au 79	7.9201	β^+	4.25
188 Hg 80	7.8992	β^+	2.29	192 Hg 80	7.9137	EC	4.24
188 Tl 81	7.8536	β^+	1.85	192 Tl 81	7.8764	β^+	2.76
188 Pb 82	7.8239	β^+	1.38	192 Pb 82	7.8548	β^+	2.32
188 Bi 83	7.7647	α	-0.68	192 Bi 83	7.8041	β^+	1.57
				192 Po 84	7.7702	α	-1.48
189 W 74	7.9527	β^-	2.84				
189 Re 75	7.9618	β^-	4.94	193 Re 75	7.9243	?	
189 Os 76	7.9630		16.10%	193 Os 76	7.9363	β^-	5.03
189 Ir 77	7.9561	EC	6.06	193 Ir 77	7.9381		62.70%

A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %	A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %
193 Pt 78	7.9338	EC	9.20	197 Hg 80	7.9087	EC	5.36
193 Au 79	7.9242	β^+	4.80	197 Tl 81	7.8937	β^+	4.01
193 Hg 80	7.9080	β^+	4.14	197 Pb 82	7.8715	β^+	2.68
193 Tl 81	7.8851	β^+	3.11	197 Bi 83	7.8413	β^+	2.75
193 Pb 82	7.8544	β^+	2.08	197 Po 84	7.8060	β^+	1.73
193 Bi 83	7.8137	β^+	1.83	197 At 85	7.7626	α	-0.46
193 Po 84	7.7738	α	-0.38				
				198 Ir 77	7.8975	β^-	0.90
194 Os 76	7.9320	β^-	8.28	198 Pt 78	7.9143	$\beta\beta$	7.20%
194 Ir 77	7.9285	β^-	4.84	198 Au 79	7.9087	β^-	5.37
194 Pt 78	7.9360		32.90%	198 Hg 80	7.9116		9.97%
194 Au 79	7.9192	β^+	5.14	198 Tl 81	7.8902	β^+	4.28
194 Hg 80	7.9149	EC	10.15	198 Pb 82	7.8791	β^+	3.94
194 Tl 81	7.8837	β^+	3.30	198 Bi 83	7.8421	β^+	2.79
194 Pb 82	7.8656	β^+	2.86	198 Po 84	7.8178	α	2.03
194 Bi 83	7.8194	β^+	1.98	198 At 85	7.7695	α	0.62
194 Po 84	7.7888	α	-0.41	198 Rn 86	7.7373	α	-1.19
194 At 85	7.7373	α	-1.40				
				199 Pt 78	7.9024	β^-	3.27
195 Os 76	7.9187	β^-	2.59	199 Au 79	7.9070	β^-	5.43
195 Ir 77	7.9249	β^-	3.95	199 Hg 80	7.9054		16.87%
195 Pt 78	7.9267		33.80%	199 Tl 81	7.8942	β^+	4.43
195 Au 79	7.9215	EC	7.21	199 Pb 82	7.8758	β^+	3.73
195 Hg 80	7.9097	β^+	4.55	199 Bi 83	7.8500	β^+	3.21
195 Tl 81	7.8913	β^+	3.62	199 Po 84	7.8111	β^+	2.52
195 Pb 82	7.8574	β^+	2.95	199 At 85	7.7792	α	0.86
195 Bi 83	7.8285	β^+	2.26	199 Rn 86	7.7411	α	-0.21
195 Po 84	7.7914	α	0.67				
195 At 85	7.7465	α	-0.20	200 Pt 78	7.8993	β^-	4.65
				200 Au 79	7.8987	β^-	3.46
196 Os 76	7.9123	β^-	3.32	200 Hg 80	7.9060		23.10%
196 Ir 77	7.9142	β^-	1.72	200 Tl 81	7.8898	β^+	4.97
196 Pt 78	7.9266		25.30%	200 Pb 82	7.8818	EC	4.89
196 Au 79	7.9150	β^+	5.73	200 Bi 83	7.8485	β^+	3.34
196 Hg 80	7.9145	$\beta\beta$	0.15%	200 Po 84	7.8278	β^+	2.84
196 Tl 81	7.8881	β^+	3.82	200 At 85	7.7840	α	1.63
196 Pb 82	7.8737	β^+	3.35	200 Rn 86	7.7551	α	-0.02
196 Bi 83	7.8322	β^+	2.49				
196 Po 84	7.8049	α	0.76	201 Pt 78	7.8859	β^-	2.18
196 At 85	7.7525	α	-0.60	201 Au 79	7.8952	β^-	3.19
				201 Hg 80	7.8976		13.18%
197 Ir 77	7.9091	β^-	2.54	201 Tl 81	7.8914	EC	5.42
197 Pt 78	7.9161	β^-	4.85	201 Pb 82	7.8780	β^+	4.53
197 Au 79	7.9157		100.00%	201 Bi 83	7.8550	β^+	3.81

A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %	A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %
201 Po 84	7.8268	β^+	2.96	205 Ra 88	7.7073	α	-0.68
201 At 85	7.7938	α	1.95				
201 Rn 86	7.7573	α	0.85	206 Hg 80	7.8692	β^-	2.69
201 Fr 87	7.7114	α	-1.32	206 Tl 81	7.8718	β^-	2.40
				206 Pb 82	7.8754		24.10%
202 Au 79	7.8862	β^-	1.46	206 Bi 83	7.8534	β^+	5.73
202 Hg 80	7.8969		29.86%	206 Po 84	7.8406	β^+	5.88
202 Tl 81	7.8863	β^+	6.03	206 At 85	7.8091	β^+	3.26
202 Pb 82	7.8822	EC	12.22	206 Rn 86	7.7892	α	2.53
202 Bi 83	7.8528	β^+	3.79	206 Fr 87	7.7478	α	1.20
202 Po 84	7.8350	β^+	3.43	206 Ra 88	7.7200	α	-0.62
202 At 85	7.7954	β^+	2.26				
202 Rn 86	7.7695	α	1.00	207 Hg 80	7.8476	β^-	2.24
202 Fr 87	7.7192	α	-0.47	207 Tl 81	7.8668	β^-	2.46
				207 Pb 82	7.8699		22.10%
203 Au 79	7.8809	β^-	1.72	207 Bi 83	7.8546	β^+	9.00
203 Hg 80	7.8876	β^-	6.61	207 Po 84	7.8367	β^+	4.32
203 Tl 81	7.8861		29.52%	207 At 85	7.8141	β^+	3.81
203 Pb 82	7.8775	EC	5.27	207 Rn 86	7.7880	β^+	2.74
203 Bi 83	7.8576	β^+	4.63	207 Fr 87	7.7567	α	1.17
203 Po 84	7.8329	β^+	3.34	207 Ra 88	7.7154	α	0.11
203 At 85	7.8041	β^+	2.65				
203 Rn 86	7.7639	α	1.65	208 Tl 81	7.8472	β^-	2.26
203 Fr 87	7.7295	α	-0.26	208 Pb 82	7.8675		52.40%
				208 Bi 83	7.8499	β^+	13.06
204 Au 79	7.8674	β^-	1.60	208 Po 84	7.8394	α	7.96
204 Hg 80	7.8856	$\beta\beta$	6.87%	208 At 85	7.8118	β^+	3.77
204 Tl 81	7.8801	β^-	8.08	208 Rn 86	7.7943	α	3.16
204 Pb 82	7.8800		1.40%	208 Fr 87	7.7569	α	1.77
204 Bi 83	7.8544	β^+	4.61	208 Ra 88	7.7324	α	0.11
204 Po 84	7.8391	β^+	4.10				
204 At 85	7.8035	β^+	2.74	209 Tl 81	7.8334	β^-	2.12
204 Rn 86	7.7809	α	1.87	209 Pb 82	7.8487	β^-	4.07
204 Fr 87	7.7350	α	0.23	209 Bi 83	7.8481		100.00%
204 Ra 88	7.7042	α	-1.23	209 Po 84	7.8353	α	9.51
				209 At 85	7.8148	β^+	4.29
205 Hg 80	7.8748	β^-	2.49	209 Rn 86	7.7923	β^+	3.23
205 Tl 81	7.8785		70.48%	209 Fr 87	7.7639	α	1.70
205 Pb 82	7.8744	EC	14.68	209 Ra 88	7.7332	α	0.66
205 Bi 83	7.8574	β^+	6.12	209 Ac 89	7.6955	α	-1.00
205 Po 84	7.8363	β^+	3.78				
205 At 85	7.8104	β^+	3.20	210 Tl 81	7.8136	β^-	1.89
205 Rn 86	7.7810	β^+	2.23	210 Pb 82	7.8360	β^-	8.85
205 Fr 87	7.7454	α	0.59	210 Bi 83	7.8326	β^-	5.64

A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %	A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %
210 Po 84	7.8344	α	7.08	214 Th 90	7.6925	α	-1.00
210 At 85	7.8117	β^+	4.47				
210 Rn 86	7.7967	α	3.94	215 Bi 83	7.7614	β^-	2.66
210 Fr 87	7.7632	α	2.28	215 Po 84	7.7682	α	-2.75
210 Ra 88	7.7415	α	0.57	215 At 85	7.7679	α	-4.00
210 Ac 89	7.6987	α	-0.46	215 Rn 86	7.7639	α	-5.64
				215 Fr 87	7.7533	α	-7.07
211 Pb 82	7.8170	β^-	3.34	215 Ra 88	7.7394	α	-2.80
211 Bi 83	7.8198	α	2.11	215 Ac 89	7.7195	α	-0.77
211 Po 84	7.8189	α	-0.29	215 Th 90	7.6930	α	0.08
211 At 85	7.8114	EC	4.41	215 Pa 91	7.6578	α	-1.85
211 Rn 86	7.7940	β^+	4.72				
211 Fr 87	7.7685	α	2.27	216 Bi 83	7.7440	β^-	2.33
211 Ra 88	7.7411	α	1.11	216 Po 84	7.7589	α	-0.84
211 Ac 89	7.7076	α	-0.60	216 At 85	7.7531	α	-3.52
				216 Rn 86	7.7587	α	-4.35
212 Pb 82	7.8044	β^-	4.58	216 Fr 87	7.7425	α	-6.15
212 Bi 83	7.8034	β^-	3.56	216 Ra 88	7.7374	α	-6.74
212 Po 84	7.8103	α	-6.52	216 Ac 89	7.7114	α	-3.48
212 At 85	7.7984	α	-0.50	216 Th 90	7.6977	α	-1.55
212 Rn 86	7.7949	α	3.16	216 Pa 91	7.6597	α	-0.70
212 Fr 87	7.7670	β^+	3.08				
212 Ra 88	7.7475	α	1.11	217 Po 84	7.7412	α	1.00
212 Ac 89	7.7086	α	-0.03	217 At 85	7.7447	α	-1.49
212 Th 90	7.6824	α	-1.52	217 Rn 86	7.7445	α	-3.27
				217 Fr 87	7.7378	α	-4.66
213 Pb 82	7.7850	β^-	2.79	217 Ra 88	7.7270	α	-5.80
213 Bi 83	7.7911	β^-	3.44	217 Ac 89	7.7104	α	-7.16
213 Po 84	7.7941	α	-5.38	217 Th 90	7.6908	α	-3.60
213 At 85	7.7901	α	-6.90	217 Pa 91	7.6647	α	-2.31
213 Rn 86	7.7823	α	-1.60				
213 Fr 87	7.7685	α	1.54	218 Po 84	7.7316	α	2.27
213 Ra 88	7.7466	α	2.21	218 At 85	7.7292	α	0.18
213 Ac 89	7.7157	α	-0.10	218 Rn 86	7.7388	α	-1.46
213 Th 90	7.6841	α	-0.85	218 Fr 87	7.7268	α	-3.00
				218 Ra 88	7.7251	α	-4.59
214 Pb 82	7.7724	β^-	3.21	218 Ac 89	7.7023	α	-5.97
214 Bi 83	7.7736	β^-	3.08	218 Th 90	7.6916	α	-6.96
214 Po 84	7.7852	α	-3.79	218 Pa 91	7.6592	α	-3.92
214 At 85	7.7764	α	-6.25	218 U 92	7.6408	α	-2.82
214 Rn 86	7.7772	α	-6.57				
214 Fr 87	7.7578	α	-2.30	219 At 85	7.7196	α	1.75
214 Ra 88	7.7492	α	0.39	219 Rn 86	7.7238	α	0.60
214 Ac 89	7.7159	α	0.91	219 Fr 87	7.7212	α	-1.70

A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %	A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %
219 Ra 88	7.7142	α	-2.00				
219 Ac 89	7.7006	α	-4.93	225 Fr 87	7.6628	β^-	2.38
219 Th 90	7.6838	α	-5.98	225 Ra 88	7.6676	β^-	6.11
219 Pa 91	7.6617	α	-7.28	225 Ac 89	7.6657	α	5.94
219 U 92	7.6365	α	-4.38	225 Th 90	7.6593	α	2.72
				225 Pa 91	7.6468	α	0.23
220 At 85	7.7043	β^-	2.35	225 U 92	7.6298	α	-1.02
220 Rn 86	7.7173	α	1.75	225 Np 93	7.6076	α	-2.22
220 Fr 87	7.7098	α	1.44				
220 Ra 88	7.7117	α	-1.74	226 Fr 87	7.6494	β^-	1.69
220 Ac 89	7.6924	α	-1.58	226 Ra 88	7.6620	α	10.70
220 Th 90	7.6847	α	-5.01	226 Ac 89	7.6557	β^-	5.03
220 Pa 91	7.6551	α	-6.11	226 Th 90	7.6572	α	3.26
220 U 92	7.6395	?		226 Pa 91	7.6412	α	2.03
				226 U 92	7.6320	α	-0.46
221 Rn 86	7.7013	β^-	3.18	226 Np 93	7.6048	α	-1.46
221 Fr 87	7.7033	α	2.47				
221 Ra 88	7.7012	α	1.45	227 Fr 87	7.6408	β^-	2.17
221 Ac 89	7.6906	α	-1.28	227 Ra 88	7.6483	β^-	3.40
221 Th 90	7.6761	α	-2.77	227 Ac 89	7.6507	β^-	8.84
221 Pa 91	7.6570	α	-5.23	227 Th 90	7.6475	α	6.21
221 U 92	7.6346	?		227 Pa 91	7.6395	α	3.36
				227 U 92	7.6265	α	1.82
222 Rn 86	7.6945	α	5.52	227 Np 93	7.6073	α	-0.29
222 Fr 87	7.6911	β^-	2.93				
222 Ra 88	7.6967	α	1.58	228 Fr 87	7.6307	β^-	1.58
222 Ac 89	7.6829	α	0.70	228 Ra 88	7.6425	β^-	8.26
222 Th 90	7.6767	α	-2.55	228 Ac 89	7.6392	β^-	4.34
222 Pa 91	7.6513	α	-2.54	228 Th 90	7.6451	α	7.78
222 U 92	7.6377	α	-6.00	228 Pa 91	7.6324	β^+	4.90
				228 U 92	7.6275	α	2.74
223 Fr 87	7.6837	β^-	3.12	228 Np 93	7.6044	β^+	1.79
223 Ra 88	7.6853	α	5.99				
223 Ac 89	7.6792	α	2.10	229 Ra 88	7.6290	β^-	2.38
223 Th 90	7.6687	α	-0.22	229 Ac 89	7.6333	β^-	3.58
223 Pa 91	7.6520	α	-2.19	229 Th 90	7.6347	α	11.37
223 U 92	7.6328	α	-4.74	229 Pa 91	7.6299	EC	5.11
				229 U 92	7.6208	β^+	3.54
224 Fr 87	7.6709	β^-	2.30	229 Np 93	7.6062	α	2.38
224 Ra 88	7.6800	α	5.50				
224 Ac 89	7.6702	β^+	4.00	230 Ra 88	7.6218	β^-	3.75
224 Th 90	7.6677	α	0.02	230 Ac 89	7.6227	β^-	2.09
224 Pa 91	7.6470	α	-0.10	230 Th 90	7.6310	α	12.38
224 U 92	7.6353	α	-3.05	230 Pa 91	7.6219	β^+	6.18

A X Z	B/A (MeV)	$\rightarrow$	$\log t_{1/2}$ or %
230 U 92	7.6210	α	6.26
230 Np 93	7.6019	α	2.44
230 Pu 94	7.5911	α	
231 Ac 89	7.6144	β^-	2.65
231 Th 90	7.6201	β^-	4.96
231 Pa 91	7.6184	α	12.01
231 U 92	7.6135	EC	5.56
231 Np 93	7.6022	β^+	3.47
231 Pu 94	7.5866	?	
232 Ac 89	7.6025	β^-	2.08
232 Th 90	7.6151	$\beta\beta$	100.00%
232 Pa 91	7.6095	β^-	5.05
232 U 92	7.6119	α	9.34
232 Np 93	7.5969	β^+	2.95
232 Pu 94	7.5890	β^+	3.31
233 Th 90	7.6029	β^-	3.13
233 Pa 91	7.6049	β^-	6.37
233 U 92	7.6040	α	12.70
233 Np 93	7.5953	β^+	3.34
233 Pu 94	7.5838	β^+	3.10
233 Am 95	7.5665	?	
234 Th 90	7.5969	β^-	6.32
234 Pa 91	7.5947	β^-	4.38
234 U 92	7.6007	α	0.01%
234 Np 93	7.5897	β^+	5.58
234 Pu 94	7.5847	EC	4.50
234 Am 95	7.5635	β^+	2.14
235 Th 90	7.5834	β^-	2.63
235 Pa 91	7.5883	β^-	3.17
235 U 92	7.5909	α	0.72%
235 Np 93	7.5871	EC	7.53
235 Pu 94	7.5788	β^+	3.18
235 Am 95	7.5647	β^+	2.95
235 Cm 96	7.5473	?	
236 Pa 91	7.5775	β^-	2.74
236 U 92	7.5865	α	14.87
236 Np 93	7.5792	EC	12.69
236 Pu 94	7.5780	α	7.96
236 Am 95	7.5607	β^+	
236 Cm 96	7.5502	β^+	
237 Pa 91	7.5699	β^-	2.72
237 U 92	7.5761	β^-	5.77
237 Np 93	7.5750	α	13.83
237 Pu 94	7.5708	EC	6.59
237 Am 95	7.5602	β^+	3.64
237 Cm 96	7.5465	?	
237 Bk 97	7.5266	?	
238 Pa 91	7.5589	β^-	2.14
238 U 92	7.5701	α	99.27%
238 Np 93	7.5662	β^-	5.26
238 Pu 94	7.5684	α	9.44
238 Am 95	7.5556	β^+	3.77
238 Cm 96	7.5483	EC	3.94
238 Bk 97	7.5242	β^+	2.16
239 U 92	7.5586	β^-	3.15
239 Np 93	7.5606	β^-	5.31
239 Pu 94	7.5603	α	11.88
239 Am 95	7.5537	EC	4.63
239 Cm 96	7.5433	β^+	4.02
239 Bk 97	7.5263	?	
239 Cf 98	7.5067	α	1.59
240 U 92	7.5518	β^-	4.71
240 Np 93	7.5502	β^-	3.57
240 Pu 94	7.5561	α	11.32
240 Am 95	7.5471	β^+	5.26
240 Cm 96	7.5429	α	6.37
240 Bk 97	7.5232	β^+	2.46
240 Cf 98	7.5101	α	1.80
241 Np 93	7.5443	β^-	2.92
241 Pu 94	7.5465	β^-	8.66
241 Am 95	7.5433	α	10.13
241 Cm 96	7.5369	EC	6.45
241 Bk 97	7.5237	?	
241 Cf 98	7.5069	β^+	2.36
241 Es 99	7.4848	α	0.95
242 Np 93	7.5334	β^-	2.52

A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %	A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %
242 Pu 94	7.5414	α	13.07	247 Es 99	7.4800	β^+	2.44
242 Am 95	7.5350	β^-	4.76	247 Fm 100	7.4650	α	1.54
242 Cm 96	7.5345	α	7.15	247 Md 101	7.4433	α	0.05
242 Bk 97	7.5189	β^+	2.62				
242 Cf 98	7.5094	α	2.32	248 Am 95	7.4874	?	
242 Es 99	7.4829	α	1.60	248 Cm 96	7.4968	α	13.03
				248 Bk 97	7.4907	α	8.45
243 Np 93	7.5253	β^-	2.03	248 Cf 98	7.4911	α	7.46
243 Pu 94	7.5310	β^-	4.25	248 Es 99	7.4756	β^+	3.21
243 Am 95	7.5302	α	11.37	248 Fm 100	7.4660	α	1.56
243 Cm 96	7.5270	α	8.96	248 Md 101	7.4416	β^+	0.85
243 Bk 97	7.5175	β^+	4.21				
243 Cf 98	7.5052	β^+	2.81	249 Cm 96	7.4856	β^-	3.59
243 Es 99	7.4857	β^+	1.32	249 Bk 97	7.4861	β^-	7.44
243 Fm 100	7.4638	α	-0.74	249 Cf 98	7.4834	α	10.05
				249 Es 99	7.4744	β^+	3.79
244 Pu 94	7.5248	α	15.41	249 Fm 100	7.4615	β^+	2.19
244 Am 95	7.5213	β^-	4.56	249 Md 101	7.4435	β^+	1.38
244 Cm 96	7.5240	α	8.76				
244 Bk 97	7.5115	β^+	4.20	250 Cm 96	7.4790	SF	11.45
244 Cf 98	7.5052	α	3.06	250 Bk 97	7.4760	β^-	4.06
244 Es 99	7.4833	β^+	1.57	250 Cf 98	7.4800	α	8.62
244 Fm 100	7.4677	SF	-2.48	250 Es 99	7.4685	β^+	4.49
				250 Fm 100	7.4621	α	3.26
245 Pu 94	7.5136	β^-	4.58	250 Md 101	7.4405	β^+	1.72
245 Am 95	7.5153	β^-	3.87				
245 Cm 96	7.5158	α	11.43	251 Cm 96	7.4668	β^-	3.00
245 Bk 97	7.5093	EC	5.63	251 Bk 97	7.4693	β^-	3.52
245 Cf 98	7.4997	β^+	3.43	251 Cf 98	7.4705	α	10.45
245 Es 99	7.4840	β^+	1.82	251 Es 99	7.4659	EC	5.08
245 Fm 100	7.4654	α	0.62	251 Fm 100	7.4569	β^+	4.28
				251 Md 101	7.4416	β^+	2.38
246 Pu 94	7.5066	β^-	5.97	251 No 102	7.4234	α	-0.10
246 Am 95	7.5050	β^-	3.37				
246 Cm 96	7.5115	α	11.17	252 Bk 97	7.4586	?	
246 Bk 97	7.5028	β^+	5.19	252 Cf 98	7.4654	α	7.92
246 Cf 98	7.4991	α	5.11	252 Es 99	7.4573	α	7.61
246 Es 99	7.4802	β^+	2.66	252 Fm 100	7.4561	α	4.96
246 Fm 100	7.4682	α	0.04	252 Md 101	7.4375	β^+	2.14
				252 No 102	7.4258	α	0.36
247 Am 95	7.4982	β^-	3.14				
247 Cm 96	7.5020	α	14.69	253 Bk 97	7.4520	?	
247 Bk 97	7.4990	α	10.64	253 Cf 98	7.4549	β^-	6.19
247 Cf 98	7.4932	EC	4.05	253 Es 99	7.4529	α	6.25

A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %	A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %
253 Fm 100	7.4485	EC	5.41	259 No 102	7.3998	α	3.54
253 Md 101	7.4377	β^+	2.56	259 Lr 103	7.3898	α	0.80
253 No 102	7.4220	α	2.01	259 Rf 104	7.3773	α	0.49
253 Lr 103	7.4021	α	0.11	259 Db 105	7.3595	?	
				259 Sg 106	7.3386	α	-0.32
254 Cf 98	7.4493	SF	6.72				
254 Es 99	7.4436	α	7.38	260 Md 101	7.3959	SF	6.44
254 Fm 100	7.4448	α	4.07	260 No 102	7.3967	SF	-0.97
254 Md 101	7.4312	β^+	2.78	260 Lr 103	7.3832	α	2.26
254 No 102	7.4236	α	1.74	260 Rf 104	7.3767	SF	-1.70
254 Lr 103	7.4003	α	1.11	260 Db 105	7.3561	α	0.18
				260 Sg 106	7.3424	α	-2.44
255 Cf 98	7.4382	β^-	3.71				
255 Es 99	7.4379	β^-	6.54	261 Md 101	7.3916	?	
255 Fm 100	7.4359	α	4.86	261 No 102	7.3882	?	
255 Md 101	7.4288	β^+	3.21	261 Lr 103	7.3809	SF	3.37
255 No 102	7.4178	α	2.27	261 Rf 104	7.3709	α	1.81
255 Lr 103	7.4020	α	1.34	261 Db 105	7.3565	α	0.26
255 Rf 104	7.3815	SF	0.18	261 Sg 106	7.3383	α	-0.64
				261 Bh 107	7.3159	α	-1.93
256 Es 99	7.4283	β^-	3.18				
256 Fm 100	7.4318	SF	3.98	262 No 102	7.3843	SF	-2.30
256 Md 101	7.4204	β^+	3.67	262 Lr 103	7.3733	SF	4.11
256 No 102	7.4166	α	0.46	262 Rf 104	7.3694	SF	0.32
256 Lr 103	7.3972	α	1.45	262 Db 105	7.3512	α	1.53
256 Rf 104	7.3853	SF	-2.17	262 Sg 106	7.3403	?	
				262 Bh 107	7.3141	α	-0.99
257 Es 99	7.4221	?					
257 Fm 100	7.4222	α	6.94	263 No 102	7.3755	?	
257 Md 101	7.4176	EC	4.30	263 Lr 103	7.3704	?	
257 No 102	7.4098	α	1.40	263 Rf 104	7.3627	?	
257 Lr 103	7.3969	α	-0.19	263 Db 105	7.3506	SF	1.43
257 Rf 104	7.3806	α	0.67	263 Sg 106	7.3359	SF	-0.10
257 Db 105	7.3608	α	0.11	263 Bh 107	7.3163	?	
258 Fm 100	7.4175	SF	-3.43	264 Lr 103	7.3627	?	
258 Md 101	7.4097	α	6.65	264 Rf 104	7.3605	?	
258 No 102	7.4073	SF	-2.92	264 Db 105	7.3449	?	
258 Lr 103	7.3911	α	0.59	264 Sg 106	7.3364	?	
258 Rf 104	7.3823	SF	-1.92	264 Bh 107	7.3135	α	-0.36
258 Db 105	7.3582	α	0.64	264 Hs 108	7.2974	α	-3.07
259 Fm 100	7.4075	SF	0.18	265 Lr 103	7.3589	?	
259 Md 101	7.4048	SF	3.76	265 Rf 104	7.3537	?	

A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %	A X Z	B/A (MeV)	→	$\log t_{1/2}$ or %
265 Db 105	7.3436	?					
265 Sg 106	7.3315	α	1.00				
265 Bh 107	7.3146	?					
265 Hs 108	7.2935	α	-3.05				
266 Rf 104	7.3504	?					
266 Db 105	7.3377	?					
266 Sg 106	7.3309	α	1.32				
266 Bh 107	7.3103	?					
266 Hs 108	7.2962	?					
266 Mt 109	7.2681	α	-3.10				

References

1. Particle Data Group: Eur. Phys. J. C **15**, 1 (2000)
2. G. Audi and A.H. Wapstra, Nucl. Phys. **A565**, 1 (1993); http://ie.lbl.gov/toimass.html.
3. R. B. Firestone, V. S. Shirley, C. M. Baglin, S.Y. F. Chu, and J. Zipkin: *Table of Isotopes* (Wiley, 1996); http://ie.lbl.gov/education/isotopes.htm.
4. D.H. Clark and F.R. Stephenson, *The Historical Supernovae*, Pergamon Press, Oxford, 1977.
5. A. Pais *Inward Bound*, Oxford University Press, Oxford, 1986.
6. E. Segré *From X rays to Quarks*, Freeman, San Francisco, 1980.
7. P.G. Hansen, A.S. Jensen and B. Jonson, Annu. Rev. Nucl. Part. Sci. **45** (1995) 591-634.
8. R. Hofstadter, Annu. Rev. Nucl. Sci. **7** (1957) 231.
9. K.S. Quisenberry, T.T. Scolam and A.O. Nier, Phys. Rev. **102** (1956) 1071-1075.
10. H. Hintenberger, W. Herr, and H. Voshage, Phys. Rev. **95** (1954) 1690-1691.
11. J. Stadlmann et al., Phys. Lett. B **586** (2004) 27-33.
12. H. Geissel et al., Nuc. Inst. Meth. Phys. Res. **B70** (1992) 286-297.
13. B. Franzke, Nuc. Inst. Meth. Phys. Res. **B24/25** (1987) 18-25.
14. G. Savard and G. Werth, Annu Rev. Nucl. Part. Sci **50** (2000) 119-52.
15. J. Van Roosbroeck et al., Phys. Rev. Lett. **92** (2004) 112501.
16. Th. Udem et al., Phys.Rev.Lett **79** (1997) 2646.
17. P.J. Mohr and B.N. Taylor, Rev. Mod. Phys. **72** (2000) 351-495.
18. E. G. Kessler et al., Phys.Lett A **255** (1999) 221.
19. See e.g. P. De Bièvre. et al., IEEE Trans. Instrum Meas. **46** (1997) 592-595; and [17].
20. J.K. Dickens, F.G. Percy and R.J. Silva, Phys. Rev. **132** (1963) 1190.
21. J. Sharpey-Schafer, Physics World **3** (September,1990) 31-34.
22. P.J. Twin et al., Phys. Rev. Lett **57** (1986) 811-814.
23. M. Lacombe, B. Loiseau, J.M. Richard, R. Vinh Mau, J. Côté, P. Pirès and R. de Tourreil, Phys. Rev. **C21**, (1980) 861.
24. G.M. Temmer, Rev. Mod. Phys. **30** (1958) 498-506.
25. I. Ahmad and P.A. Butler, Annu. Rev. Nucl Part. Sci **43** (1993) 71-116.
26. R.A. Carrigan et al., Phys. Rev. Lett. **20** (1968) 874-876.
27. J. Giovinacco et al., Eur. Phys. J. **10** (2001) 3-84.
28. C. E. Bemis et al., Phys. Rev. C **16** (1977) 1146-1158.
29. Yu. Ts. Oganessian et al., Phys. Rev. C **63** (2000) 011301.
30. Data from ENDF data base http://t2.lanl.gov/data/ndviewer.html.
31. H.Geissel, G. Münzenberg and K. Riisager, Annu Rev. Nucl. Part. Sci **45** (1995) 163-203.
32. R.F.Frosch et al., Phys. Rev. **174** (1968) 1380-1399.
33. R.M. Littauer, H.F.Schopper and R.R.Wilson, Phys.Rev. Lett. **7** (1961) 144-147.

34. Samuel S.M. Wong, *Introductory Nuclear Physics* Prentice Hall,Englewood Cliffs 1990.
35. J.M. Pendlebury, Annu. Rev. Nucl. Part. Sci **43** (1993) 687-727.
36. Dassié et al. Phys. Rev. D **51**(1995) 2090.
37. R.L. Graham et al., Can. Jour. Phys. **30** (1952) 459.
38. Loritz et al. Eur.Phys. J. **A6** (1999) 257-268.
39. R. Mössbauer, Z. Physik **151** (1959) 126.
40. C.Y. Fan, Phys.Rev. **87** (1952) 258.
41. H. Abele et al. Phys. Lett. B **407** (1997) 212-218.
42. S. Arzumanov et al. Phys. Lett. B **483** (2000) 15-22.
43. H. Behrens, J. Janecke: *Numerical Tables for Beta Decay and Electron Capture*, (Landolt-Bernstein, new Series, vol I/4, (Springer, Berlin, 1969).
44. J.R Reitz, Phys. Rev. **77** (1950) 50.
45. Weinheimer et al Phys. Lett. B **460** (1999) 219.
46. M. Goldhaber, L. Grodzins and A.W. Sunyar, Phys. Rev. **109** (1958) 1015.
47. M. Apollonio et al., Eur.Phys.J. C **27** (2003) 331-374.
48. K. Eguchi et al., Phys.Rev.Lett. **90** (2003) 021802 (KamLand Collaboration).
49. Y. Fukuda et al.: Phys. Rev. Lett. **81**, 1562 (1998)
50. Physics Today **56** (2003) 19.
51. M. Gell-Mann, Phys. Lett., **8** (1964) 214.
52. P. de Marcillac et al. Nature **422** (2003) 876-878.
53. G. Heusser, Annu. Rev. Nucl. Part. Sci **45** (1995) 543-590.
54. J.A. Simpson , Annu. Rev. Nucl. and Part. Sci **33** (1983), 323.
55. Energy-loss tables can be found in L.C. Northcliffe and R.F. Schilling, Nuclear Data Tables **A7** (1977) 233. See also F.S. Goulding and B.G. Harvey, Ann. Rev. Nucl. Sci. **25** (1975) 167.
56. R. Schneider et al. Zeit. Phys. A **348** (1994) 241-242.
57. www.epa.gov/radiation/students/calculate.html
58. W.F. Libby, in *Les Prix Nobel en 1960* Stockholm, 1961.
59. J. S. Lilley: *Nuclear Physics* (Wiley, Chichester, 2001).
60. G.W. Wetherill Annu. Rev. Nuc. Sci. **25**(1975) 283-328.
61. R. Cayrel et al. Nature **409** (2001) 691-692.
62. M. Smoliar et al., Science **271** (1996) 1099-1102.
63. F. Dyson in *Aspects of Quantum Thoery* edited by A. Salam and E.P. Wigner (Cambridge U. Press, Cambridge, 1972)
64. K. Olive et al., Phys.Rev. D **69** (2004) 027701.
65. B.L.Cohen, Rev. Mod. Phys **49** (1977) 1.
66. C.D. Bowman, Annu. Rev. Nucl. Part. Sci. **48** (1998) 505-556.
67. M. Maurette, "Fossil Nuclear Reactors", Annu. Rev. Nucl. Sci **26**, 319-350.
68. A. I. Shlyakhter, Nature **264**, 340 (1976). T. Damour and F. Dyson, Nucl. Phys. **B480** (1996) 37.
69. M. Junker et al., Phys. Rev. C **57** (1998) 2700.
70. A. Krauss et al., Nucl. Phys. **A467** (1987) 273.
71. D. Zahnow et al., Z. Phys. A **351** (1995) 229-236.
72. D. D. Clayton *Principles of Stellar Evolution and Nucleosynthesis* (University of Chicago Press, Chicago, 1983).
73. J. N. Bahcall, M.H. Pinsonneault and S. Basu, Ap. J. **555** (2001) 990-1012.
74. S. Turck-Chieze and I. Lopez, Ap. J. **408** (1993) 347.
75. F. Hoyle Ap. J.Supp. **1** (1954) 121-146.
76. M. Livio et al., Nat. **340** (1989) 281-284.
77. H. Oberhummer, A. Csótó,.and H. Schlattl, Science **289** (2000) 88-90.
78. R. Diehl and F. S. Timmes, Publ. Astron. Soc. Pac. **110** (1998) 637-659.

79. E. Anders and N. Grevess Geochimica et Cosmochimica Acta **53** (1989) 197-214.
80. E. M. Burbidge, G.R. Burbidge, W.A. Fowler and F.Hoyle, Rev. Mod. Phys. **29** (1957) 547.
81. Q.R. Ahmad et al., Phys. Rev. Lett. **89** (2002) 011301; Q.R. Ahmad et al., Phys. Rev. Lett. **89** (2002) 011302.
82. S. Fukuda et al., Phys. Rev. Lett. **86** (2001) 5651.
83. B.T. Cleveland et al., Ap. J. **496** (1998) 505-526.
84. W. Hampel et al., Phys. Lett. B **447** (1999) 127.
85. J. N. Abdurashitov et al., Phys. Rev. C **60** (1999) 055801.
86. J.N. Bahcall and M.H. Pinsonneault, Phys. Rev. Lett. **92** (2004) 121301.
87. K. Hirata et al. Phys. Rev. Lett. **58** (1987) 1490-1493.
88. R.M. Bionta et al. Phys. Rev. Lett. **58** (1987) 1494-1497.
89. J.F. Beacom, W.M. Farr and P.Vogel, Phys.Rev. **D66** (2002) 033001.
90. B.J.Teegarden, Astr. J. Supp. **92** (1994) 363-368.
91. A.F.Iyudin et al., Astron. Astrophys. **284** (1994) L1-L4.
92. J. Mather et al.: Astrophy. J. **512** (1999) 511.
93. D. Tytler et al.: Physica Scripta **T85**, 12 (2000).
94. C.L. Bennett et al., Astrophys.J.Suppl. **148** (2003) 1.
95. S. Perlmutter et al.: Astrophy. J. **517**, 565 (1999)
96. B. Schmidt et al.: Astrophy. J. **507**, 46 (1998)
97. B.F. Madore et al.: Astrophy. J. **515**, 29-41 (1999)
98. R. Cen and J. P. Ostriker: Astrophy. J. **514**, 1 (1999)
99. Combes, F. and D. Pfenniger: Astron. Astrophys. **V**, 453 (1997)
100. A.G. Cohen, A. De Rujula and S.L. Glashow: Astrophy. J. **495**, 539 (1998)
101. P. Smith and J. Lewin: Phys. Rep. **187**, 203 (1990)
102. J. Ellis et al.: Phys.Rev. D **62**, 075010 (2000)
103. D.S. Akerib et al., Phys. Rev. **D68** (2003) 82002; A. Benoit et al., Phys. Lett. B **545** (2002) 43.
104. E. Vangioni-Flam, A. Coc and M. Casse: Astron. Astrophys. **360**, 15 (2000); H. Reeves, J. Audouze, W. Fowler, and D. Schramm, Ap. J. **179** (1973) 909.
105. S. Burles and D. Tytler: *Stellar Evolution, Stellar Explosions and Galactic Chemical Evolution, Second Oak Ridge Symposium on Atomic and Nuclear Astrophysics* (IOP,Bristol, 1998).
106. K. A. Olive, G. Steigman and T. P. Walker: Phys. Rep. **333**, 389 (2000)
107. M. Rauch et al.: Astrophy. J. **489**, 7 (1997)

Index