

Health Physics 3321 Radiologic Physics

Spring Semester Class Time: Friday 1:00 - 2:50 Place: TBD

Text:

Steward C. Bushong;

Radiologic Science for Technologists, Physics, Biology, and Protection (latest edition)

Instructor: Richard R. Brey Ph.D., C.H.P. /Professor of Health Physics AVP Operations and Safety
Office: CH 234 Telephone: 282-2667

Office Hours: Monday through Thursday 10:00 to 11:00 or by appointment. Informal open door policy.

Course Description:

PHYS 321 Radiologic Physics (2 credits) Basic Physics of x-ray production and the interaction of x-rays with matter. Includes topics in medical imaging. Available to juniors in Radiographic Sciences.

PREREQ: PHYS 1100. S

Tentative Course Schedule

TOPIC READINGS (Bushong)

Grading Policy, Testing Format, Homework Policy, Expectations.

Basic Radiation Physics

Physics/Mathematics Review

Concepts of matter/ atomic and nuclear structure

Radioactive decay

Class Notes

Types of Radiation

Interactions of Radiation with matter

Fundamentals of Radioactivity

Test 1

Generation, interactions, and behavior of characteristic and

Continuous X-Rays

Test 2

Health Physics practice, instrumentation & dosimetry

Regulations

Class Notes

Radiobiology

Test 3 (Cumulative Final)

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HPHY 3321 Class Policy

1) Homework will represent 30% of the overall class grade.

a) Homework should be expected frequently.

i) Students are encouraged to work together on homework.

ii) Homework problems can and may be the basis for test questions.

iii) Homework assignments are not considered to be group projects.

Each student should do their own work, merely consulting with others as appropriate.

- A photocopy of the work of someone else is not acceptable.

** The instructor is a resource during office hours or by appointment.

b) All homework assignments must be completed.

i) Students who don't complete all homework assignments can expect an incomplete

grade in the course at the discretion of the instructor.

c) Questions completed correctly will be awarded an appropriate number of points.

Assignments will typically include several multi-part questions or inter-related questions.

* Students are encouraged to write out the assigned questions.

* All work is to be shown.

* The student is encouraged to carry units along with the solution of the problem, and provide a neat easy to follow answer.

- homework which is too difficult to follow will be returned with a zero grade until completed in an acceptable fashion.

* Answers must be given with the appropriate units.

* All answers are to be circled.

2) There will be two full lecture period tests and a cumulative final examination.

a) Tests will cover topics on homework, lectures, and assigned reading.

b) Each test will be worth 20% of the final class grade.

c) The cumulative final examination will be worth 30% of the final class grade.

d) At the discretion of the instructor, any evidence of dishonesty are grounds

for failing tests or examinations, and subject to other university disciplinary actions.

3) Final Class grade

a) Grades will be based on:

Homework	30%
Tests	40%
Final	30%

b) Tentatively, grades will be earned based on a straight scale grading policy:

≥ 97%+A
≥ 93%A
≥ 90%-A
≥ 87%+B
≥ 83% B
≥ 80%-B
≥ 77%+C
≥ 73%C etc.

c) The instructor reserves the right to change the grading scale, and assignment weighing. Such changes will be:

- i) based on profession judgement
- ii) applied across the board to all students
- iii) in favor of the students

4) Reading assignments should be completed prior to lecture.

a) Students are encouraged to apply the SQ3R study method.

SQ3R:

Survey the literature

Develop Questions prior to reading and based on the survey

Read the material answering your own questions

Recite what was read

periodically Review the material

6) Lectures:

- a) Bring pertinent questions on the literature, personal experiences, and current affairs, which do not have self-evident answers, to lecture.
- b) Students can expect to be asked questions about the topics at hand while attending lecture so please be prepared.
 - i) This lecture style is intended to build student confidence.
 - It is not intended to embarrass, intimidate, or belittle, students. It is okay not to have an answer, but not okay to leave it at that.
- c) Take advantage of the opportunities available - You have paid for them!

Idaho State University is committed to providing equal opportunity in education for all students. If you have a diagnosed disability or if you believe you have a disability (physical, learning, hearing, vision, psychiatric) that might require reasonable accommodation in this course, please contact the Disability Services Center, Rendezvous Building, Room 125 (282-3599) or on the web at <http://www.isu.edu/ada4isu.edu>. It is the responsibility of students to contact instructors during the first week of each semester to discuss appropriate accommodations.

Academic integrity is expected of all individuals. Behavior beyond reproach must be the norm. Academic dishonesty in any form is unacceptable. Academic dishonesty includes, but is not limited to, cheating and plagiarism. Procedures for determination of academic dishonesty and imposition of penalties for academic misconduct are outlined in the [Student Code of Conduct](#).

Health Physics 3321 Radiologic Physics

Introduction and Definitions

Matter is anything that occupies space.

We consider matter to be composed of atoms.

Atoms are composed of neutrons, protons, and electrons.

We categorize atoms into different types referred to as elements. For example hydrogen, oxygen, carbon.

Elements vary according to the number of protons contained within the nuclei of their atoms.

The number of protons in an atom largely determine its properties. The properties of atoms with different numbers of protons vary in a predictable fashion.

We have developed the Periodic Table of the Elements based upon this observation.

There are variations of the atom types within elements. Although any atom of an element will have the same number of protons, the number of neutrons within atoms of a particular element may vary.

Elements of atoms (all having the same number of protons) but with different numbers of neutrons are referred to as isotopes of an element. Hence we have C-14, C-13, C-12.

Overview of the Atom

A) Consideration of the electron

1. Electrons are considered to be fundamental particles.
2. they move in a wavelike motion about the nucleus.
 - (a) this is described using wave mechanics.

(b) this motion is confined to specific geometric orbitals which are a definite distance from the nucleus.

(c) these distances are referred to as energy states or energy levels. Only certain states are allowed.

(d) one may speak of the probability of finding an electron at a given distance from the nucleus or at a certain energy level.

3. The mass of the electron is about $1/1837$ that of the hydrogen atom or about $9.1 \times 10^{-28} \text{g}$.

4. The electron, because of its electromagnetic nature does not have a definite radius.

(a) any measurement of the electron's radius will be somewhat dependent on the experimental procedure used.

(b) the radius of the electron is taken to be less than $1 \times 10^{-16} \text{cm}$.

5. The charge of the electron:

(a) It was once thought that the quantity of charge carried by an individual electron could not be further divided.

(b) there is evidence that this is no longer the case. It is now known that smaller units of charge than the possessed by the electron exist.

(i) The evidence of this is the existence of quarks.

(ii) Six different quarks and their anti-quarks have been named these are:

NAME	Approximate Mass		
	(grams)	(GeV/c ²)	Electrical charge
up (u)	7.1×10^{-27}	4×10^{-3}	$2/3$
down (d)	1.2×10^{-26}	7×10^{-3}	$-1/3$
charm (c)	2.7×10^{-24}	1.5	$2/3$
strange (s)	2.7×10^{-25}	0.15	$-1/3$
top (t)	1.6×10^{-22}	>0.89	$2/3$
bottom (b)	8.4×10^{-24}	4.7	$-1/3$

note; the top quark has not yet been observed.

Quark theory along with several conservation laws can be used to explain the composition and behavior of many of the elementary particles thought to exist.

Families of Elementary Particles

Fundamental particles are composed of elementary particles.

There are several ways to classify elementary particles.

Elementary particles can be classified according to:

1) The types of interactions the particles undergo during their reactions and decay.

a) weak interactions

b) electromagnetic interactions

c) nuclear or strong interactions

2) According to their rest mass

a) Lightest group: Leptons

b) Middle mass group: Mesons

c) Heaviest group: Baryons

3) Intrinsic spins

4) Life times of those particles that are unstable with respect to decay

a) as a rule the stronger the forces involved, the shorter the half-life:

Interaction Type	Typical Half-life range
Strong Interactions	10^{-23} to 10^{-20} s
Electromagnetic Interactions	10^{-18} to 10^{-15} s
Weak Interactions	10^{-10} s to 15 min

5) nature of the associated antiparticle

The classification scheme which encompasses many of the others employs segregation by rest mass. This scheme includes the Lepton, Meson, and Baryon families. The following table summarizes this classification scheme of elementary particles.

Consideration of the Nucleus

A) The nucleus is composed of protons and neutrons. The collective term for these is nucleons.

B) Nucleons are a sub-set of the baryon family of elementary particles.

(a) They have relative long half-lives compared to other members of the baryon family and are consequently considered to be stable.

C) A proton is similar to the nucleus of the ordinary hydrogen atom (protium).

(a) It is positively charged.

(b) A proton may be thought of consisting of two up quarks and one down quark.

(c) The magnitude of the charge is the same as that on the electron.

(d) Its mass is 1836 times that of an electron. or about $1.6726485 \times 10^{-24} \text{g}$

D) Originally it was thought that nuclei were merely multiples of the proton.

1. Under this false assumption the mass number of the hydrogen proton was assigned a value of one.

2. Accordingly the mass numbers of subsequent nuclei should have simply been merely multiples of the hydrogen proton.

3. However, the nuclear mass numbers were found to be about twice as great as the corresponding atomic numbers.

(a) This ratio became relatively greater as the atomic numbers increased.

E) Another problem with the assumption that the nucleus was composed entirely of protons was an inconsistency, and subsequent need to account for the stability of the nucleus, when the Coulombic forces among the nuclear protons

1. Consider a simple calculation comparing the Coulombic force of repulsion and the gravitational force of attraction acting between two protons.

(a) The Coulombic force of repulsion is given as:

$$F = k_0 q_1 q_2 / r^2$$

(b) The gravitational force of attraction is given as:

$$F = Gm_1m_2/r^2$$

2. It is clear when considering the magnitude of these two forces that unless some other forces are involved that an atom composed of protons should not be capable of existing.

F) This enigma was solved by James Chadwick in 1932 when he discovered the neutron

1. The neutron has roughly the same mass as the proton, but its mass is just slightly greater than that of the proton.

2. The proton's mass is $1.6726485 \times 10^{-27} \text{kg}$

3. The neutron's mass is $1.6749544 \times 10^{-27} \text{kg}$.

4. A neutrons mass is about 1837 times that of an electron.

G) The neutron is thought to be composed of two down quarks and one up quark.

H) A neutron has no charge; it is electrically neutral.

(ii) A description of the neutron in terms of fundamental particles indicates (as mentioned above) that the neutron consists of two down quarks and one up quark.

(iii) This combination gives it a neutral charge.

(I) The presence of neutrons within an atom supplies the attractive nuclear forces otherwise known as the strong forces.

1. Nucleons are bound together in the nucleus by the action of the nuclear force.
2. Nuclear forces are cohesive force acting over extremely short ranges (2 to 3×10^{-13} cm) which holds the nucleus together overcoming the repulsive Coulombic forces discussed above.
3. The strong force or nuclear force is thought to be generated by the exchange of gluons with quarks.
4. The strong force or nuclear force is one of the basic forces of nature.

(J) The four basic forces in nature are:

1. Gravitational force - between two masses
2. Electromagnetic force - charged particles.
3. Weak forces - beta decay processes.
4. Strong forces - Nuclear force.

In field theory it is thought that the force arising between objects arises from the exchange of certain particles.

- 1) The strong (sometimes called the nuclear) interaction between nucleons is thought to arise from the interchange of pi-mesons or pions.
- 2) The graviton is thought to be interchanged by objects having gravitational attraction.
- 3) The vector boson carries the weak interaction.

4) The electromagnetic field is carried by photons.

5) Quarks are thought to be held together by the exchange of particles whimsically named gluons.

CONVENTIONS FOR DESCRIBING NUCLEONS

A) In an undisturbed atom the number of extranuclear electrons is equal to the number of protons.

B) The atom as a whole is electrically neutral.

C) The number of protons in the nucleus of an atom determines the type of element.

D) This number is called the atomic number of the element.

1. Atomic number has the designation Z.

One may alternately say a particular substance has a high z or a high atomic number.

E) The number of protons plus neutrons in the nucleus of an atom is called the mass number.

1. The mass number is designated by the letter A.

F) The number of neutrons is equal to $A - Z$ and is called the neutron number.

1. The neutron number is designated by the letter N.

G) The mass number of the nucleus of an atom is not the same as its atomic mass.

1. The atomic mass of an atom is the mass of the atom compared to the mass of ^{12}C .

^{12}C mass = 12 amu.

^{12}C was adopted in 1962.

2. That is to say that the modern scale of atomic and molecular weights is set by stipulating that the gram atomic weight of the carbon 12 isotope, ^{12}C , is exactly 12.000g.

H) The radius of the nucleus of an atom of atomic mass number A is given approximately by the formula:

$$r = 1.3A^{1/3} \times 10^{-13} \text{ cm}$$

1. The radii of atoms are about $1 \times 10^{-8} \text{ cm}$
2. The radii of nuclei are about 10^{-13} cm to 10^{-12} cm .

I) Although the nucleus is small compared to the atom, the nucleus contains all the mass of the atom. An atom is mostly empty space.

Consider the following analysis:

We know that the volume of a sphere is equal to $\frac{4}{3}\pi r^3$ hence the ratio of the:

$$\text{Volume of atom/volume of the nucleus} = \frac{[\frac{4}{3}\pi(10^{-8})^3]}{[\frac{4}{3}\pi(10^{-12})^3]} = 10^{12}$$

The correction for the volume of electrons is negligible. Therefore, only 1 part in about 10^{12} is matter.

This reality is important to keep in the back of your mind particularly when we start to speak about the interaction of radiation with matter.

(J) It is good to remember that matter, the items we call solid objects for instance, are predominantly composed of empty space. The density of nuclear matter, the material in the nucleus - the nucleons - is about 10^8 tons/cm^3 .

1. The emptiness of the atom is the reason small particles can penetrate matter.

(K) We should all remember that a gram atomic weight of any element contains Avogadro's number, $N_0 = 6.023 \times 10^{23}$, of atoms.

1. And that a gram molecular weight of any gas contains Avogadro's number of molecules and occupies a volume of 22.4136L at standard temperature and pressure. (e.g. 273K and 760 torr where 1 torr=1 mm Hg).

(L) Each species or nucleus is designated by its nuclear composition this may be observed in its proper designation.

1. The most commonly used method of designation was approved in 1960 by the International Union of Pure and Applied Chemistry (IUPAC)

(J.A.M.Chem.Soc.82,5526(1960)).

2. A full designation uses the following items:

Symbol for the element: the central point of the designation

Mass number: left upper index

Atomic number: left lower index

Ionic charge: right upper index

Number of atoms in molecule: right lower index.

Example:

Which may be found in the molecule $\text{Ca}_3(\text{PO}_4)_2$.

Usually the atomic number is omitted since the symbol for the element designates the number of protons.

It should also be noticed that the ionic charge is indicated as $n+$ rather than $+n$, where n is some integer.

In some of the older literature the mass number is written as a right upper index.

This was done primarily in the United States. This method is no longer used.

3. Another acceptable method is to write the element name or write out the elemental symbol followed by the mass number, for example:

Ca-45

or

Calcium-45.

(M) Originally it was thought that for a given element all of the atoms were identical.

1. It is now known that even for a given element there can be many different species.
2. The different species differ in the number of neutrons present in the nucleus.
3. These different species are called isotopes.

Note: Do not refer to isotopes alternately as species the words are not interchangeable it is done here for discussion purposes only.

Isotopes are species of nuclei with the same atomic number but different mass number.

Examples of isotopes are as follows:

${}^9\text{C}$ ${}^{10}\text{C}$ ${}^{11}\text{C}$ ${}^{12}\text{C}$ ${}^{13}\text{C}$ ${}^{14}\text{C}$ ${}^{15}\text{C}$ ${}^{16}\text{C}$

4. Isotopes are species of the same element.
5. The chemical and physiological properties of an element depend upon the number of electrons.
6. The isotopes of a given element all have the same number of electrons.
 - (a) Therefore, for practical purposes the chemical and physiological properties of all the isotopes of an element are the same.However, at low Z a small mass effect may be observed in some circumstances.

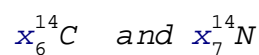
(b) This is the basis for using isotopes as tracers in chemical and biological work.

Examples: The thyroid uses iodine, ^{127}I is stable.

If we give someone ^{131}I instead of ^{127}I this difference cannot be distinguished by the thyroid.

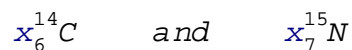
However, we can detect the radiation emitted from ^{131}I and study the iodine uptake kinetics of a thyroid.

(N) Isobars are species of nuclei with the same mass number but different atomic number.



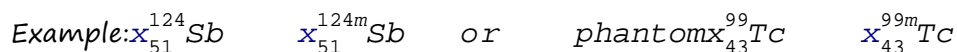
Example:

(O) Isotones are species of nuclei with the same number of neutrons.



Example:

(P) Isomers are species of nuclei with the same atomic and mass numbers but with different energy levels.



1. These are called metastable isomers because they have measurable half-lives.

(Q) A Nuclide is any species of nucleus characterized by its composition, in particular by the number of protons and neutrons, but also the energy level of the nucleus.

1. The term nuclide is a general term.

2. It should always be used when no relationship to another nuclear species is intended.

Example:

C-12 may be referred to as a nuclide.

C-12 and *C-13* are isotopes.

C-12 is an isotope of carbon.

They are isotopic to each other.

C-14 and *N-14* are isobars.

C-14 and *I-131* are nuclides. Except for being radioactive they are not related.

The term isotope is commonly misused.

(R) There are presently (as of November 29, 1993) 109 elements recognized by the American Chemical Society.

(S) The combinations of neutrons and protons which are stable are called Stable Nuclides.

1. Those nuclides which are rare, on the atom percentage basis present in the natural mixture, can be used as tracers.

2. These are referred to as rare stable isotopes.

(a) However, the use of rare stable isotopes is a complicated technique requiring highly sensitive, and expensive, equipment such as mass spectrometers.

(T) Elements with atomic number through 92 (uranium) exist in nature with the exception of 43 (Technetium) and 61 (promethium).

1. Elements with atomic numbers 93 and 94 have been separated from pitchblende in very small amounts.

(a) These result from neutron interactions.

(U) Elements with atomic numbers 93 (Neptunium) through 109 have been synthesized.

1. Many more will probably be synthesized.

(V) All elements greater than 83 (Bismuth) are radioactive.

1. These radionuclides have no stable isotopes.

(W) There are several elements with atomic numbers 83 and less that are naturally radioactive because they contain small percentages of naturally radioactive isotopes.

1. To exist in nature a radioactive nuclide must either:

(a) Be continuously produced by some process

(b) Have a half-life comparable to the age of the earth, somewhere around 4.5×10^9 y.

X) Those combinations of neutrons and protons which are not stable are called radioactive nuclides or simply radionuclides.

1. Their instability may be overcome by a transformation in the nucleus leading to a different species of nucleus.

2. This transformation is called radioactive decay.

All things being equal, the essential aspect of matter that we can realize is mass.

In physics we actually realize three fundamental base quantities:

1) Mass

- 2) Length
- 3) Time

Base quantities allow us to describe objects.

Mass is defined as the quantity of matter contained within an object. The MKS system uses the unit of kilograms to measure quantities of mass.

Mass should not be confused with the idea of weight.

Weight actually is the experience of force.

You should remember that

Force = Mass x Acceleration

The unit of force in the MKS system is the newton. An object with a 10 kg mass on the planet earth is associated with a force of:

$$F = (10\text{kg})(9.80\text{m/s}^2) = 98.0 \text{ kg}\cdot\text{m/s}^2 = 98.0 \text{ Newtons}$$

where 9.80m/s^2 is the acceleration due to the force of gravity experienced on the planet earth.

In the old English system, the acceleration due to the force of gravity experienced on the planet earth is 32.2 feet/s^2

The unit for mass is the slug. Force is given in units of pounds.

What is your mass in slugs?

If you were on the Moon, would your mass change?

Would your weight change in these two circumstances?

The unit second is used to measure time.

The unit meter is used to measure length. A meter is defined as the wavelength of orange light emitted from an isotope of krypton, Kr-86.

We use base quantities to develop derived quantities.

Derived quantities are concepts that allow us to describe experiences, such as motion.

The derived quantities of greatest interest are:

Velocity

Acceleration

Force

Momentum

Work

Energy

Power

Velocity is simple length divided by time.

Acceleration is the rate of change of velocity.

Force is the product of mass and acceleration.

Momentum is the product of mass and velocity

Work is the product of force and distance

Power is the quotient of work divided by time.

Energy is the ability to do work. We experience energy in either the form of Kinetic Energy or Potential Energy.

We can say that kinetic energy is the energy of motion.

$$\text{Kinetic energy} = (1/2)mv^2$$

Potential Energy is the capacity to do work.

$$\text{Potential energy} = \text{mass} \times \text{acceleration} \times \text{height}$$

Your book describes several situations in which we commonly experience either kinetic energy or potential energy:

Form of energy

Way it is experienced

Chemical Energy

Electrical Energy

Thermal Energy

Nuclear Energy

Electromagnetic energy

Heat is defined as the kinetic energy of randomly moving molecules. The calorie is the unit of heat. A calorie is the energy necessary to raise one gram of water one degree Celsius. In dieting we often talk about calories but we are actually referring to kilocalories.

Temperature is a scalar measurement of heat; we commonly use two different unit systems for measuring temperature. The Celsius scale and the Fahrenheit scale. A third absolute scale exist referred to as the Kelvin scale. At sea level, water boils at 100°C , 212°F , and 373 K . At sea level water freezes at 0°C , 32°F , and 273 K .

Heat energy is transferred in three ways,

1) Conduction:

2) Convection:

3) Thermal radiation:

Conduction is the transfer of heat energy along or between touching objects. Convection is the mechanical transfer of heat energy by rapidly moving gas or liquid.

Radiation: Energy emitted from a source as waves or particles and transmitted through space.

Radioactivity: The phenomenon of spontaneously emitting radiation as a result of changes in the nuclei of atoms that are energetically unstable.

This change is called Radioactive decay or radioactive disintegration or just decay or disintegration.

The word spontaneous is important. Nuclei can be made to change into different nuclei, but the change is not spontaneous.

Example: Co-60

A) Transformation Kinetics

1. The rate of transformation of a radionuclide, the rate of decay, is a first order reaction.
2. The rate of decay is a function of the number of radioactive elements present in a sample.
3. More formally, the rate of decay (dN/dt) is proportional to the total number N of atoms in a radioactive sample:

$$\frac{dN}{dt} \propto N \quad \text{where:}$$

dN/dt = the number of atoms decaying per unit of time, the rate of decay.

N = the total number of atoms present

4. It can be observed that the number of radioactive atoms decreases as time passes.

5. With this information we can make a specific statement:

$$\frac{dN}{dt} = -\lambda N$$

(a) This is the instantaneous rate of decay at any time.

(b) The negative sign N decreases as the time increases.

(c) λ is called the decay constant.

(i) The decay constant is a property of each radionuclide.

(ii) The rate of decay is not altered by any known physical or chemical means. Neither pressure, temperature, chemical changes, gravitational fields, electrical fields, nor magnetic fields, effect the rate of decay.

(d) Radioactive decay is a random process.

(e) We can never determine when an individual atom will decay.

(f) Given a population of atoms we can predict when a fraction of the population is likely to decay.

(g) Radioactive decay is a stochastic process.

(h) If we consider a population of atoms, and plot the number of atoms which decay in each finite increment of time following some initial starting point this plot will have a Poisson distribution.

(B) The rate of decay is actually used to describe the quantity of radioactive material present.

1. We may call the rate of decay the activity (A) of the sample.

2. The old unit of activity is the Curie (Ci).

(a) Originally the unit curie was based in the measured number of atoms disintegrating per unit time from one gram of Ra-226.

(i) This unit was named in honor of the Curies who discovered radium.

(b) Today, one curie is defined to be equal to 3.7×10^{10} disintegrations/second.

(c) Here we are using the word disintegration interchangeably with the word transformation.

3. The SI unit of activity is the becquerel (Bq).

(a) A becquerel is one disintegration per second.

(b) There are 3.7×10^{10} Bq per 1.0 Ci.

$$1.0 \text{ Ci} = 3.7 \times 10^{10} \text{ Bq}$$

(c) Alternately, we may write:

$$A = \frac{dN}{dt} = -\lambda N$$

4. This in itself is a useful expression, given any two variables in this equation we can determine the instantaneous value of the third variable.

(a) For instance, using this equation we can determine the instantaneous number of atoms present in a sample given the activity and the value of λ .

(b) The equation:

$$\frac{dN}{dt} = -\lambda N$$

is a first order differential equation.

(c) We can solve this equation as follows:

First separate variables:

$$\frac{dN}{N} = -\lambda dt$$

Then we integrate both sides of the equation:

$$\int \frac{dN}{N} = \int -\lambda dt$$

this result of this operation is:

$$\ln(N) + \text{Const}_1 = -\lambda t + \text{Const}_2$$

where \ln is the natural log function.

lets allow $\text{Const}_2 - \text{Const}_1$ to equal $\ln(C)$, doing so allows the equation to be rewritten as:

$$\ln(N) = -\lambda t + \ln(C)$$

We know as an initial condition that at time is equal to 0, $t = 0$ and we can denote the number of atoms at time equals 0 as N_0 hence, the equation becomes:

$$\ln(N_0) = 0 + \ln(C)$$

therefore; $\ln(N_0) = \ln(C)$, or $N_0 = C$. We can rewrite the equation as:

$$\ln(N) = -\lambda t + \ln(N_0)$$

this is the same as:

$$\ln(N) - \ln(N_0) = -\lambda t$$

which is the same as:

$$\ln\left(\frac{N}{N_0}\right) = -\lambda t$$

raising both sides by \exp yields:

$$\frac{N}{N_0} = \exp^{-\lambda t}$$

This expression is sometimes called the exponential radioactive decay law.

Incidentally, since $A = -\lambda N$ we may also write this as:

$$\frac{A}{A_0} = \exp^{-\lambda t}$$

$$A_0 \exp^{-\lambda t}$$

5. The number of disintegrations which have occurred over a period of time

$$A_0 \exp^{-\lambda t}$$

may be found by integrating the expression:

wrt to time from the beginning of the time of interest (t_1) to the end of the time of interest (t_2) as follows:

$$\int_{t_1}^{t_2} A_0 e^{-\lambda t} dt = \left[\frac{A_0}{-\lambda} e^{-\lambda t} \right]_{t_1}^{t_2}$$

When $t_1 = 0$ this becomes:

$$\frac{A_0}{\lambda} (1 - e^{-\lambda t_2})$$

6. We have already mentioned that the decay constant is a property of each radionuclide.

(a) There are several different ways to describe the decay constant.

(b) Consider a plot of the ratio of A/A_0 versus time.

(c) It can be observed that A/A_0 decreases as a smooth function of time.

(i) This is the exponential decay function.

(ii) If we look at any ratio of A/A_0 and then at the ratio $(0.5)(A/A_0)$ we can define the time it takes for one-half of atoms of a particular radionuclide to decay.

(iii) This time is the radionuclide's half-life.

(iv) Sometimes the half-life is called the physical half-life.

(7) The half-life can be used to describe the decay constant.

(a) Initially, we can state that in one half-life ($t_{1/2}$) only one half of the activity we had initially (A_0) will be present.

(b) That is to say that the ratio of A/A_0 will be one half of the original value

(c) Under these conditions the exponential radioactive decay law can be written as:

$$\frac{1}{2} = e^{-\lambda t_{1/2}}$$

taking the natural log of both sides of the equation produces:

$$\ln\left(\frac{1}{2}\right) = -\lambda t_{1/2}$$

this is equal to:

$$-0.693 = -\lambda t_{1/2}$$

consequently:

$$\lambda = \frac{0.693}{t_{1/2}}$$

(d) This is one definition of the decay constant.

8. The half-life of a radionuclide is commonly found in the literature.

(a) Several sources include:

The Chart of the Nuclides

The Health Physics and Radiological Health Handbook

The CRC Handbook of Chemistry and Physics

The Radiological Health Handbook (of 1970)

9. Another methods of describing the decay constant is sometimes also encountered.

(a) This is the average or mean life (τ):

(i) The average or mean life is the reciprocal of the decay constant

(i.e)

$$\tau = 1/\lambda.$$

10. Hypothetically, one could speak of the tenth-life or fifth-life or any other such thing.

(a) Such a parameter would be defined similarly to the half-life parameter.

11. It is interesting to point out two items when discussing the exponential radioactive decay law and the half-life.

(a) First since the exponential decay law describes exponential decay and since exponential function never reaches 0, items which are radioactive will always be radioactive theoretically.

(b) That being said what does it mean.

It means that if we had billions and billions of radioactive atoms we cannot predict when the very last atom in the population will decay (nor exactly when any atom in the population will decay).

The exponential function is asymptotic to the zero value.

(c) The expression $\exp^{-\lambda t}$ can be thought of as the probability of a number of atoms decaying within a certain period of time.

(i) As t gets large this probability becomes very small.

(d) As a rule of thumb we say that after the tenth half-life a radioactive material is considered to decay away "completely".

(i) This obviously applies when dealing with medium to small sources of radioactivity.

(ii) For very large sources of radioactivity even after the tenth half-life there may still be a considerable amount of radioactive material present relatively speaking.

12. A second interesting item is an argument:

(a) Some argue that every atom in the universe is in reality radioactive.

(b) What we refer to as stable species simply have half-lives which are so long that we can not measure them.

(c) Students are encouraged to think about this idea for a while.

(i) Half-life values for radionuclides range from fractions of a (i.e. 10^{-13} s) second to billions of years (i.e. 2×10^{18} y - Bi-209).

Wilhelm Konrad Roentgen (Germany) is given credit for his November 8, 1895 discovery of x-rays.

While working with a Crooke's tube Roentgen notices that a small nearby screen coated with barium platinocyanide fluoresced when the Crooke's tube was operated.

Roentgen recognized that this was caused by a previously unknown agent which he named x rays.

Within a few days he was able to describe the basic properties of x rays.

- 1) High penetrating power in light materials
- 2) Stronger absorption in soft tissue and bone.
- 3) X rays affected photographic plates.
- 4) X rays are not deflected by magnetic fields
- 5) X rays caused an electroscope to lose its charge

Taking advantage of these properties Roentgen developed the famous picture, shown in your text which contrasts the differential absorption of x rays in soft tissue and bone.

Henri Becquerel (France) was given credit for his 1896 discovery of Radioactivity.

While studying the phosphorescence of potassium uranyl sulfate he observed that a crystal of this salt darkened a photographic plate even when this assembly was kept in the dark.

- 1) It was found that the source of this radiation was the uranium metal itself.
- 2) The radiation was emitted spontaneously in apparently undiminished intensity.
- 3) This radiation could discharge an electroscope.

In 1898 Pierre (France) and Marie (Poland) Curie started an intensive study of radioactive material.

They observed that thorium was also radioactive. They found that pitchblende (an ore containing about 75% U_3O_8) contained two new elements which were much more strongly radioactive than uranium. These elements were polonium and radium.

Polonium is named in honor of Poland, Marie Curie's country of origin. Radium is a Latin word indicating radius - ray.

The discovery of x rays was a scientific bombshell. Experimenters and physicians, laymen and physicists set up x-ray generating apparatus and proceeded about their labors with seemingly lack of concern regarding potential dangers.

There was nothing in previous experience to suggest that x rays would be potentially dangerous. How could a ray which was undetectable by human senses be damaging to a person?

Soon after the widespread and unrestrained use of x rays began, deleterious human effects were reported.

- 1) Reports of skin erythema, epilation, and similar effects began to appear in the literature early in 1896.
- 2) Blood changes, tumor induction, and leukemia were reported in the early decades following the turn of the century.

By the turn of the century the first organizations to study the potentially harmful effects of radiation were established.

These were followed by a string of committees who are still periodically producing and publishing scientific reports on the health effects and safety recommendations concerned with the use of radiation by humans.

- 1) 1899 (three years after discovery of x rays) the British Roentgen Society.

- 2) 1900 American Roentgen Ray Society (ARRS) founded.
- 3) 1915 British Roentgen Society adopts x-ray protection resolution.
- 4) 1920 ARRS establishes standing committee for radiation protection.
- 5) 1921 British X-ray and Radium Protection Committee presents its first radiation protection rules.
- 6) 1922 ARRS adopts British rules.
- 7) 1925 First International Congress of Radiology establishes ICRU.
- 8) 1928 ICRP established under auspices of the Second International Congress of Radiology.
- 9) 1931 The roentgen adopted as unit of x-radiation.
- 10) 1934 ICRP recommends daily tolerance dose.
- 11) 1942 Manhattan District begins work on first atomic bomb.
- 12) 1946 U.S. Atomic Energy Commission created.
- 13) 1946 NCRP formed.
- 14) 1948 NCRP introduces recommendations and introduces risk/benefit concept.
- 15) 1953 ICRU Introduces concept of absorbed dose.
- 16) 1955 Health Physics Society formed.
- 17) 1955 UNSCEAR established.
- 18) 1956 ICRP lowers basic permissible occupational dose to present.
- 19) 1958 First UNSCEAR report.
- 20) 1977 ICRP 26 published.
- 21) 1978 ICRP 30 published.
- 22) 1980 BEIR III published.
- 23) 1988 BEIR IV published.
- 24) 1990 BEIR V published.

Sources of Radiation Exposure

Humans are now, and have always been, continuously exposed to ionizing radiation.

This radiation comes from natural radionuclides in the earth's crust, from cosmic sources including cosmically produced radionuclides, and from human activities.

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Sources of radiation exposure

Terrestrial radiation

1) natural decay chains

A) Three natural decay chains

a) Uranium series (U-238)

b) Thorium series (Th-232)

c) Actinium Series (U-235)

B) Totally 46 types of nuclides are involved in these three decay chains.

C) Radon is a member of the uranium decay chain.

D) A fourth series no longer occurs naturally this is the Neptunium series (Pu-241).

2) Singly occurring radionuclides

A) There are at least _____ types of naturally occurring radionuclides.

B) Most radiometrically important singly occurring radionuclides.

a) _____

b) _____

Cosmic radiation

A) Galactic radiation

a) Direct exposure: high energy particles, the majority of which are stopped in the atmosphere, produces some direct exposure.

b) The process of stopping high energy particles in the atmosphere produces secondary particles which contribute significantly to human radiation exposure.

c) Cosmic secondary particles beside being a source of direct exposure may interact with atoms in the atmosphere or on earth to produce cosmogenic radionuclides. There are several cosmogenic, radionuclides the four most radiometrically important radionuclides produced in this fashion include:

- i) _____
- ii) _____ (also known as tritium)
- iii) Na-22
- iv) Be-7

B) Solar radiation

- a) Normally stopped in the earth's magnetic field.

Anthropogenic

General categories of human activities which produce radiation or radioactive material increasing population exposure

- A) Medical arts
- B) Industrial processes and testing
- C) Scientific research
- D) Energy generation
- E) Military applications

Fractions of total human radiation exposures from various sources

Reference NCRP 160: "Reprinted with permission of the National Council on Radiation Protection and Measurements, <http://NCRPonline.org>).

NCRP says: that there is a total dose received by all Americans of about 187,000,000,000 person-millirem.

- There are about 300,000,000 Americans

- Hence the average dose delivered is about 620 millirem

This is a factor of about 1.7 times higher than the average estimated in 1980.

The difference is mostly associated with increased medical exposures.

The distribution in dose among individuals is heavily skewed

Annual exposure to external sources of radiation in North America – 120 mrem

Annual exposure to internal and external sources of radiation exposure about 620 mrem

Typical chest x-ray 30 mrem

Typical dental x-ray 10 mrem to head

Annual occupational limit for radiation workers 5,000 mrem (5 rem)

LD_{50/30} 450,000 mrad (450 rad)

SPECIFIC ACTIVITY

1. *The concept of specific activity can sometimes be useful to express exactly how much radioactive material is present in a particular sample.*

2. *Neither the Becquerel nor curie, although used as a unit of quantity, mention anything about the mass or volume of the radioactive material in which the specified number of transformations occur.*

3. The concentration of radioactivity, or the relationship between the mass of radioactive material and the activity_____.

4. Specific activity is the quantity of activity divided by a unit volume or unit mass.

5. The specific activity of a _____ radioisotope, that is a radioisotope that is not mixed with any other isotope of the same element, may be calculated as follows:

$$\text{Specific Activity} = \frac{(0.693)(6.022 \times 10^{23}) \frac{\text{atoms}}{\text{moles}}}{(t_{1/2}) A \frac{\text{g}}{\text{moles}}}$$

$$\text{Specific Activity} = \frac{(\lambda)(6.022 \times 10^{23}) \frac{\text{atoms}}{\text{moles}}}{A \frac{\text{g}}{\text{moles}}}$$

where:

A is the atomic weight of the isotope

and λ is expressed in s^{-1} , $t_{1/2}$ in units of s.

1) Properties of Ionizing Radiation

Introduction

There are three common types of radiation emitted from the nucleus of radionuclides. These radiations are sometimes called ionizing radiation because they can cause the ionization of matter, they have sufficient _____ or impart sufficient _____ to produce ion pairs.

1) Alpha particles - α

alpha
a. Alpha particles are equivalent to the nucleus of the helium atom. The alpha particle consists of _____ protons and _____ neutrons which are tightly bound together. The alpha particle is a very stable particle.

2) Beta Particles - β

a. There are two kinds of beta particles:

(1) Negatrons - β^- , e^-

The negatron is a negatively charged electron indistinguishable from the electron ordinarily found in matter.

(2) Positrons - β^+ , e^+

3) Gamma rays - γ

a. Gamma rays are a type of _____ radiation. Gamma rays are similar to x rays.

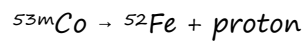
(1) The difference between gamma rays and x rays is their origins.

gamma rays originate from the nucleus of the atom.

x rays are generated within the electron orbitals of the atom.

4) In addition to the three types of radiation listed above there are a few radionuclides which emit either protons or neutrons.

(a) for example:



Emission of protons is rare.

(b) ${}^{252}\text{Cf}$ undergoes spontaneous fission.

Although this is fission rather than radioactive decay it is an example of a the release of neutrons.

11) Modes of Radioactive Decay:

1) Radioactive nuclides decay by one of several modes.

(a) Each radionuclide has its own characteristic sequence of decay modes.

A) Alpha Transitions

1) When an alpha particle is emitted during radioactive decay it may or may not be accompanied by a gamma ray.

(a) Alpha decay does not occur in nuclei with $A \leq 140$.

(b) It is thought that all nuclei with $A \geq 140$ undergo alpha decay, but for some the decay rate is so slow that alpha particle emission has not been detected.

(c) Alpha decay schemes are usually complicated:

2) During alpha decay, A decreases by 4 and Z decreases by 2.

3) Because of the requirement that A _____, alpha decay does not occur in nuclides frequently used in biological work.

a. Alpha emitters are high in the periodic table.

b. These elements in general are not used in biological systems and in fact are usually toxic to biological systems.

B) Isobaric Transitions

Isobaric Transitions does not lead to a change in A but it does cause a change in Z .

1. One definition of beta decay is that it is a decay leading to a change in _____ without a change in _____.

2. Gamma ray emission may or may not accompany beta decay.

3. There are three common types of Isobaric Transitions.

a. Negatron decay occurs when there is a _____ n/p ratio.

- formed.
- (1) During negatron decay Z increases by one and an isobar is formed.
 - (2) In beta decay transitions occur between isobar.
 - (3) In negatron emission, there is a transition of a nucleon from its neutron to its proton energy state.
 - (4) The negatron is emitted at high velocities.
 - (5) An _____ is emitted simultaneously with the negatron during negatron decay.
 - (6) Both the negatron and the antineutrino are created as the instant they are emitted since they cannot exist as such in the nucleus.
 - (7) During negatron decay, recoil of the nucleus is negligible.

Example: P-32 a pure negatron emitter.

More commonly, excited states are formed after negatron emission. These excited states loose energy by gamma emissions.

(8) Negatron emission is common with reactor produced radionuclides.

(a) Reactor produced radionuclides generally have high n/p ratios.

b. Positron decay occurs in nuclei with _____ n/p ratios.

(1) During positron decay Z decreases by one.

(2) Positron decay leads to isobar formation.

(3) During positron emission, there is a transition of a nucleon from its proton to its neutron energy state.

(4) The positron is emitted at high velocities.

(5) During positron decay both a positron and a _____ are emitted simultaneously.

(6) Both the positron and the neutrino are created at the instant they are emitted since they cannot exist as such in the nucleus.

(7) In positron emission there is always a _____-MeV difference in the kinetic energy of the positrons and the Q value.

a. The reason is that the parent atom loses a positron in the nuclear transition and the daughter atom loses an electron to become electrically neutral since Z decreases by one.

b. An energy of 1.02 MeV is equivalent to the _____ of an electron and a positron.

(8) Positron emission cannot occur unless Q is at least _____ MeV.

(9) Positron emission is common with accelerator produced radionuclides, many of these have _____ n/p ratios.

c. Electron capture, sometimes known as K-capture, is an alternate mode of decay to positron emission.

(1) Electron capture occurs when there is a _____ n/p ratio.

(2) Electron capture decreases Z by one.

(3) Electron decay results in isobar formation.

(4) During electron capture the nucleus captures an extranuclear electron, usually from the K-level.

its

a. In the nucleus, a nucleon is transformed from its proton to neutron energy state.

b. The neutrino is the only radiation that is emitted from the nucleus (unless the daughter is formed in an excited state).

c. There can also be L-capture, but this is less probable than K-capture.

[1] Electrons at the K-level are more likely than any other to be found near the nucleus.

* The amplitude of the wave function of a k-level electron is higher near the nucleus than that of an L-level electron.

[2] If Q is less than the binding energy of the K-level electrons, then only L-capture can occur.

(5) The capture of an electron leaves a vacancy in the level from which the electron was captured.

a. This vacancy is filled by an electron from the next higher energy level.

b. This electron readjustment produces _____ of the product nucleus.

(6) Rather than an x ray being emitted, the energy may be transferred to an electron at a higher energy level.

a. This electron is then emitted with an energy equal to the characteristic x-ray energy minus its own binding energy.

b. The electron emitted is called an _____ electron.

Example: In the decay of Fe-55, x rays and auger electrons are the only radiations emitted from the atom, other than the neutrino. Had the daughter, Mn-55 been formed in an excited state, gamma rays would be emitted. Auger electrons have such low energies that they are usually not detected by the common radiation detectors. Neutrinos react poorly with matter. Consequently, only x rays can be detected.

Example: Na-22, frequently, electron capture and positron emission occur together.

(7) Generally, the Q value for both positron emission and electron capture is listed as Q_{EC} on the decay scheme.

a. This practice avoids misunderstandings as to whether or not the rest mass of the positron and negatron is included in the Q value for positron emission.

(8) If the Q value for a nuclide with a low n/p ratio is less than 1.02 MeV, only electron capture can occur.

(9) Above 1.02 MeV, positron emission competes with electron capture more effectively the higher the Q value.

(10) On the other hand, _____ in atomic number favor electron capture. With high Z, positron emission is rare. The potential barrier against positron emission increases with Z.

a. The reason is that with higher Z, electron orbits are smaller, and there is a greater probability for an electron to be within the nuclear volume.

c. The overall process where by an energetically excited nucleus releases energy without a change in the structure of the nucleus, just a decrease in the energy level of the nucleus is known as Isomeric transition.

1) During _____ transition there is no change in A or Z.

(a) The nucleus goes from an excited energy state to a lower energy state or a ground state.

2) The transitions between excited states of nuclei usually occur within a very short time, probably about 10^{-13} to 10^{-16} seconds.

(a) These transitions proceed in accordance with the exponential decay law and have a characteristic half-life.

(b) If these half-lives are measurable, the excited states are called isomers, or metastable

isomers.

3) There are two categories of Isomeric transition:

(a) When the excited nucleus emits a gamma ray and goes to a lower energy state or to a ground state this is called _____ transition.

(b) Radiative transition can be sub-divided into two processes:

i) Gamma ray emission is the emission of one photon from the nucleus.

ii) When two gamma rays are emitted within a very short period of time from the same radionuclide these are called _____ gamma rays. These must be emitted from the same nuclide and there may be two or more.

4) A second type of isomeric transition is called _____.

5) During _____ the nucleus interacts with an _____ electron.

(a) This electron may be in the K, L, M, etc., level but the K level predominates. The reason is the same as for electron capture.

(b) The electron is emitted with an energy equal to the disintegration energy minus its own binding energy.

These electrons are called _____ electrons.

(c) Both x ray and auger electrons accompany internal conversion. Both are produced in a manner identical to their production in electron capture.

(d) In internal conversion the excited nucleus interacts electromagnetically with the electron. No gamma ray is produced.

(e) Internal conversion is an alternate to _____.

(f) frequently, a nuclide decays by both isomeric transition and internal conversion.

(g) The internal conversion coefficient is the ratio of the number of conversion electrons to the number of gamma rays emitted.

(1) It is designated by the symbol α or e/γ . It may have any value between 0 and ∞ .

(h) Internal conversion is favored by _____ atomic number and by _____ Q values.

d. Less common modes of decay.

1) Proton Emission (very rare)

2) Spontaneous fission (this process occurs only with very heavy elements).

(a) Delayed neutron emission occurs with nuclides with a high n/p ratio.

(b) In such a negatron is emitted first.

(c) The product nucleus is left with an energy in excess of the binding energy of one of its neutrons.

(d) Several neutrons are emitted promptly, these are referred to as prompt neutrons.

(e) Other neutrons are emitted in a very short time after fission and these neutrons are referred to as a delayed neutron.

(1) Delayed neutrons are used in the control of nuclear reactors.

Properties of Electromagnetic Radiation

A. Both Gamma-rays and X-rays are a types of electromagnetic radiation.

1. There are many types of electromagnetic radiations:

- a. Visible light
- b. Infrared light
- c. ultraviolet light
- d. gamma rays
- e. x rays

2. Electromagnetic radiations consist of oscillating _____ and _____ fields.

a. A field is a region where a certain kind of force is exerted.

3. All electromagnetic fields can travel at the same velocity.

a. This is the velocity of light:

b. $c = 3.0 \times 10^{10} \text{ cm/s} = 3.0 \times 10^8 \text{ m/s}$

(1) this is the velocity of light in a vacuum

c. The energy of electromagnetic radiation is proportional to the frequency of oscillation of the electric and magnetic fields:

$$E = hf = h\nu$$

E = energy in ergs

h = Planck's constant (6.625×10^{-27} erg-sec).

$\nu = f$ = frequency of radiation s^{-1} .

d. Frequency is inversely proportional to the wavelength:

$$f = c/\lambda$$

c = velocity of light

λ = wavelength of wave (cm)

4. The energy of electromagnetic radiation is quantized.

a. This was proposed by the quantum theory.

b. The energy of electromagnetic radiation is carried in little "bundles" or packets.

(i) Each little bundle or packet is called a photon or quantum.

(ii) The energy of a photon or quantum is given by the expression

$$E = hf = h\nu \text{ or } E = hc/\lambda.$$

(iii) A photon cannot be further subdivided. It either exists, or it disappears completely when it undergoes various interactions.

5. Photons are classified by their _____, not their energy.

a. Photons involved with radioactive nuclides include gamma rays and x rays.

b. The gamma rays from radioactive nuclides have energies that range from about 10 keV to about 3 MeV.

c. There are two types of x rays:

i) characteristic x rays, which are emitted from extranuclear electrons in transitions between different energy levels. Their energies range from a few keV up to a about 100 keV (a little higher for the artificial elements).

ii) Bremsstrahlung or continuous x rays; these are emitted during acceleration of charged particles, usually electrons (beta particles).

Their energies range from zero up to some maximum value. These maximum values are the energies of the charged particles which emit bremsstrahlung.

d. Gamma rays are monoenergetic.

i) Their energy depends on the nuclear transitions which form them.

ii) There can be more than one energy group even for a given radionuclide. Within each group all the gammas have the same energy.

e. Characteristic x rays are monoenergetic. Their energies depend upon the energy level transitions from which they originated.

f. Bremsstrahlung radiation is not _____. It exhibits a continuous spectrum.

6. Gamma rays and x rays interact with matter in essentially the same manner.

a. Both interact with matter _____ compared to alpha and beta particles.

b. gamma and x rays can penetrate great thicknesses of matter.

7. Gamma rays and x-rays have no charge.

a. Gamma rays do not have the same force fields that are associated with charged particles.

b. The fact the gamma rays do not have mass is immaterial since gravitational force generally is not significantly involved in the interaction of radiation.

8. Gamma rays do not produce excitation and ionization in the same manner that charged particles do.

a. They cannot lose their energy in small amounts, since they must give up all their energy or none at all.

9. Gamma rays do have an electromagnetic force field.

a. This force field allows gammas to interact with matter.

b. Electromagnetic radiation interact with matter in three principal ways:

i) The photoelectric effect

- some start to undergo _____ at an attempt in regeneration.
* At higher doses these attempts at regeneration usually fail or abort.
These clusters of dividing cells regress and disappears.

- Later in time regeneration will again begin. Precursors of red and white cells will appear after a general hyperplasia which characterizes this "real" regeneration. This regeneration does not mean the animal will escape death.

3. Lymphoid tissue is also severely effected by the dose-range that produces the hematopoietic syndrome. The required dose for this is less species dependent than that of the hematopoietic syndrome.

i. Shortly after the a total-body dose:

- the node become severely depleted of cells.
- node architecture is completely disrupted

ii. Regeneration of the nodes occurs soon after irradiation, and usually in a rapid fashion.

Cytologic Changes

1. One aspect of the Hematopoietic system is a predictable change in the mitotic frequency in the bone marrow.

i. Initially the mitotic frequency drops.

ii. The mitotic frequency then rises. The time at which the rise occurs is very much a function of the absorbed dose.

- The slope of the rise in frequency is also a function of dose.

- The rapid rise in mitotic frequency results in an overshoot of the normal frequency.

iii. There is then a second fall in the mitotic frequency in the bone marrow which in turn is followed by a second rise. Eventually, the mitotic frequency is restored to the normal unirradiated frequency.

2. Many of the cells in a rebounding populations are abnormal.

i. However, a large number of abnormal cells are not readily apparent in the regenerating bone marrow.

- Undoubtedly, some of the damaged chromosomes are quickly repaired.

- More likely, many of the injured cells are quickly eliminated.

- Some cells with damaged chromosomes survive and continue to multiply.

* These can be detected many years later.

3. Within a few hours after irradiation and well before bone-marrow regeneration a range of nuclear abnormalities of cells in the bone marrow may be observed.

i. The nuclei of some of these cells may be shrunken, their chromatin will be clumped.

ii. The nuclei of others will appear faint, as if their chromatin were diluted or dissolving. These cells are dying, the injury from radiation has killed them even before they were able to divide.

iii. Some cells will display aberrant chromosomes.

- some chromosomes will be swollen

+ Chromosome bridges will be present

+ Broken chromosomes will be present.

+ Some cells will have spindles with more than two poles.

+ Other grossly- abnormal cells will be present at this time.

- Most of these directly damaged cells will be quickly eliminated.

-The elimination of cells directly following irradiation is primarily responsible for the loss of total cellularity in marrow.

h. The Latent Period

1. Degenerative changes in the bone marrow and attempts at early regeneration occur during the prodromal and the latent periods.

2. Death, as a result of the hematopoietic syndrome, is believed to be due to the loss or failure of the bone marrow to carry out its function; supplying the organism with the functional cells that it needs in its circulating blood.

i. There is a direct loss of some red and white blood cell precursors.

ii. There is a later loss of some of the remaining red and white blood cells due to injury to their nuclei (mutations and chromosome aberrations).

iii. There is an inhibition of mitosis at various times post irradiation.

3. The combination of these three processes results in a critically short supply of circulating cells, this is true for several reasons:

i. Circulating cells have limited life spans.

ii. Most circulating cells are highly specialized.

iii. Most circulating cells do not divide.

- The body depends on stem cells of the bone marrow, a set of undifferentiated frequently dividing cells.

+ The stem cells are the cells which are directly eliminated.

i. The Blood Count

1. The loss of precursor cells in the bone marrow is reflected in the number and kinds of cells in the circulating blood.

2. After irradiation, there is a drop in blood count (anemia); its severity depends on dose.

3. Anemia, as associated with the hematopoietic syndrome does not arise initially from the destruction of bone marrow and the subsequent drop in the production of red cells.

- There is a drop in the production of red cells but this is not initially noticeable as mature blood cells have relatively long life.

- Red cells are lost from circulation because of:

+ a large number of small hemorrhages into tissue (petechiae) related to the breakdown of the capillary walls.

+ More importantly, there is a deficiency in the number of platelets resulting in an increase in clotting time.

j. Infection is the terminal phase of the hematopoietic syndrome.

1. fever is common.

- temperature rise above 105° F are typical.
- overwhelming infection can be expected.

2. Normal intestinal flora have been isolated as an infectious agent in large animals.

3. Bacteremia in the blood stream of smaller animals is expected.

- This has not been observed in man, probably because of differences in analysis techniques, although they may be present.

4. Infection greatly influences the time course of survival of irradiated mammals.

5. Treatment of animals with antibiotics both prior to irradiation or post irradiation increases their mean survival time.

- Germ free animals have been shown to have higher survival rates for given radiation doses than animals that are not germ free.

6. It may be concluded that the irradiated animals receiving large doses of radiation have increased susceptibility to organisms not normally pathogenic and normally pathogenic.

- Infection, therefore, is extremely important in regard to the mortality associated with irradiation.

- Infection after total body irradiation is correlated with the loss of circulating blood cells namely granulocytes.

7. Death associated with the hematopoietic syndrome is related to:

- a failure of the bone marrow.
- failure of the body systems to combat infection.

8. The effects of irradiation on immunity

- The immune system is responsible for the bodies defence against harmful environmental agents.
- The immune system can be viewed as being composed of two categories, an innate system and an acquired system.
 - + The innate category is a product of genetic makeup and is an expression of the experiences of past generations.
 - + Acquired defense is related to an individuals own experience.
- The fundamental aspect of the immune system is the antigen-antibody reaction.
 - + Immune response is initiated when a foreign body, referred to as an antigen enters the body and stimulates the lymphoid-macrophage system.
- Under appropriate conditions the antigen stimulates the formation of antibodies.
 - + These are specific proteins which have the ability of neutralizing or reacting with the antigen.
 - + Antibodies are antigen specific. An antibody capable of defeating one type of antigen is ineffectual against another type of antigen.
 - + The specific antibodies formed after the initial antigen insult are maintained and spring into action if that specific antigen again challenges the body. This is referred to as acquired immunity.
 - +The initial response may be relatively slow the first time a particular antibody is formed. Due to acquired immunity, any subsequent response is expected to occur in a much more rapid and effective fashion.
- Radiation acts as an immunologic suppressive

- + Because the lymphoid system is in the same range of radiosensitivity as the hematopoietic system, whole body radiation at high doses results in a rapid death of large numbers of lymphocytes and inhibition of cellular reproduction in many others.
- + In mammals, doses of whole body radiation on the order of 500 rads will cause rapid degeneration of lymphoid cells.
- + Active proliferation of lymphoid cells does not restart until 3 or 4 weeks post irradiation.
- + If an antigen is introduced after irradiation, the formation of antibodies is delayed until the capacity for mitotic activity is recovered.
- + Cells that are actively synthesizing antibodies may continue to be active even after massive doses of radiation.
- + Acquired immune responses are relatively resistant to radiation, however, the appearance of antibodies may be delayed following a large acute dose to radiation.
- + The depression of the immune response following exposure to large doses of ionizing radiation can be significantly modified by partial shielding of the lymphoid tissue in the body or by the injection of living lymphoid cells after the irradiation event.
- + The depression in the immune response probably plays the largest role in the death of exposed animals. This is primarily related to enhanced susceptibility to infection.

R. The gastrointestinal syndrome

1. The primary manifestations of the gastrointestinal syndrome are the failure of two systems:

- The cells lining the intestinal tract (the mucosa)
- The cell renewal system of the bone marrow.

2. The true or complete gastrointestinal syndrome can be obtained only after total-body irradiation.

3. However, irradiation of the gastrointestinal tract alone can be fatal, but the full syndrome must involve the cell renewal system of the bone marrow as well.

4. The syndrome demonstrates the following initial signs after irradiation:

- a. Lack of appetite
- b. sluggishness
- c. diarrhea
- d. signs of infection and dehydration
- e. loss of weight
- f. retained food and water in the stomach for long periods of time
- g. very low absorption of the food eaten.

5. At the same time the number of circulating white blood cells will drop to nearly zero.

6. The terminal phase of the syndrome happens rapidly, often lasting for less than a day, it includes:

- a. Severe diarrhea
- b. severe dehydration
- c. distinct emaciation
- d. vomiting
- e. essentially inert behavior

7. Death will occur with regularity in most species between 3 and 4 days after irradiation.

It will be observed post mortem that:

- a. Blood volumes have changed
- b. Electrolyte levels in the serum will be altered
- c. There will be evidence of bacteremia (bacteria in the blood) in many species.
- d. Severe wasting and dehydration

- e. Stomachs will show the retention of food and water
- f. The small bowel itself may be swollen and may contain a bile colored, bad smelling, liquid tainted with blood
- g. The large bowel may contain liquid stools that are often bloody
- h. There will be a large quantity of mucus in the gut
- i. The mucosal layer of the small intestine will be badly damaged
 - The villi will be flattened and shrunken
 - Some areas will lack the cellular lining altogether
 - Many of the crypts which are usually active in cell proliferation will be empty
- j. In the stomach and rectum, some areas will be denuded of cells and will be ulcerated
- k. The bone marrow is formless, completely without structure.

8. Cellular structure of the gastrointestinal tract.

- a. The mature functional cells of the gut epithelium are those lining its villi, in particular at the ___ of the villi.
- b. The crypts, much like the bone marrow, are _____ centers. Crypt cells are:
 - i. Undifferentiated
 - ii. In general, unspecialized
 - The specialized functional cells of the villi (in particular those of the small intestine) have a short life.
 - Normally they wear out and are sloughed into the intestinal lumen only a few days after they become functional.
- c. The gut lining may be said to undergo _____ renewal.
 - i. The cells of the crypt:
 - have a high _____ rate

- are the source of replacement of the rapidly renewing epithelial lining.

ii. There is an orderly procession of cells from the crypts up the villi through a region in which they mature, through another in which they function, to the villus tips where they are extruded and sloughed.

Schematic diagram of the regions of a normal intestinal villus

d. As in the case of the bone-marrow syndrome, radiation strikes at the cells that are the source of differentiated functional cells.

1. This is to be expected because:

- These cells are most frequently active in mitosis
- These cells are most frequently active in DNA synthesis.
- These cells are undifferentiated.

e. Effects of irradiation on the cellular mitosis with the small intestine.

1. After irradiation the rate of cellular mitosis drops drastically.

- In many species there will be no cells undergoing mitosis _____minutes post exposure.

2. The length of time for which mitosis is inhibited is a function of dose.

- The larger the dose the longer mitosis will be _____.

3. It is expected that the mitotic rate will rise sharply after the inhibition time has passed. This will be followed by a second depression in the

mitotic rate. This is similar to the circumstances expected in the bone marrow post irradiation.

- Many of the cells taking part in the first "increased mitotic rate" have nuclear abnormalities such as broken, lagging, or sticky chromosomes.

- These cells and most of their progeny die after _____

4. Death is thought to occur in an irradiated animal by the gastrointestinal syndrome if a critical number of crypt cells become irradiated.

5. Cells in the bone-marrow are grievously damaged by doses producing the gastrointestinal syndrome.

- damage to the bone marrow is an integral part of the gastrointestinal syndrome.

- The bone-marrow renewal systems are completely depleted within a few days after irradiation at the gastrointestinal syndrome level.

- Consequently, there is a major lack of important hematopoietic cells, primarily _____, when the brunt of the gastrointestinal syndrome's signs occur.

9. Degenerative Changes in the Lining of the Small Intestine.

a. The following changes may be observed after exposures large enough to experience the gastrointestinal syndrome:

CRYPT CELLS

- i. Within the first day one may observe progressive destruction in the nuclei of the cells that line the crypts of the intestine.

- The chromatin agglomerates into an _____ masses which is densely straining.

ii. Both the nuclei and cytoplasm swell, some dissolution may be observed within the damaged cells.

iii. The dead and dying cells produce a measurable decrease in the number of cells of the _____ lining.

i. The cells which remain have abnormal nuclei and are often swollen and enlarged.

iv. Few crypt cells are observed to be in mitosis, this is unusual because crypt cells normally have a high rate of mitosis. Those cells in mitosis are often abnormal.

v. Initially one observes many dead crypt cells, but eventually they are sloughed off and are passed down the intestine.

i. Since mitosis is occurring at a slow rate these dead cells are not replaced and areas void of cells appear.

ii. The cells remaining often appear abnormal.

INTESTINAL VILLI

vi. The villi of the intestinal wall begin to lose cells progressively with time. They begin to shorten and shrink.

i. The rate of cell loss is proportionally to the magnitude of dose.

vii. At death, the villi are nearly flat and almost completely free of living cells.

b. The precise time schedule of these effects and the time required prior to observing them depends on:

i. Total dose

ii. Species

c. The intestine can be expected to be denuded of cells in most mammals who have received a "gastrointestinal syndrome sized dose" in _____. For man this is typically up to 4 or 5 days post irradiation.

10. Regeneration in the Gastrointestinal Tract.

a. Even after extremely large doses of radiation not every crypt cell is going to be killed.

i. Some which remain will be severely damaged and unable to reproduce.

ii. Some which remain will be heavily damaged but still able to reproduce.

- These cells will form the nucleus on a focus of regeneration of the gut.

iii. Unfortunately, at gastrointestinal syndrome sized doses the attempt at regeneration is too little too late.

- At lower doses ranges, say between the hematopoietic and gastrointestinal syndrome ranges, _____ regeneration doses occur

iv. During regeneration the following occurs:

- There is an increase in the mitotic rate

- Epithelial linings of the crypt begin to be repopulated from the cells still capable of division.

- The newly regenerated cells begin to move into the villi to replace those that have been sloughed.

- New nest of cells start to appear, these represent new crypt.

v. If the dose is very low, clearly within the hematopoietic syndrome range, it is possible for regeneration of the whole intestinal lining to occur.

- However, this does not preclude death associated with _____.

11. The remainder of the small intestine undergoes a pattern of changes similar to those observed in the small bowel.

a. The main difference is that the changes occur more slowly so that, when death comes following a gastrointestinal syndrome sized dose, the large intestine is rarely completely denuded of its epithelium.

b. This is consistent with the renewal requirements and turnover of mature cells in the large and small bowels.

12. Fluids and Electrolytes:

a. When near death, animals experiencing the gastrointestinal syndrome, suffer from profound _____.

- The reduction in body fluids is so severe that the blood becomes exceedingly thick. Some observe that obtaining blood samples is even difficult in this situation.

b. Fluid loss/electrolyte imbalance is attributed to several concurrent items:

- _____.

- _____ This prompts severe fluid loss.

* It is thought that this is brought about by the inability of the distal end of the small intestine (distal ileum) to reabsorb bile salts and the resulting irritation of the colon by these salts.

** diarrhea has been prevented in irradiated animals clamping the bile duct.*

- _____

13. Infections: Animals irradiated to dose-levels resulting in the gastrointestinal syndrome may be expected to become infection prone.

- Infection plays a major role in causing the death of animals exposed to large enough dose to cause the gastrointestinal syndrome.

- In order to evaluate the potential for infection during the gastrointestinal syndrome one needs only consider the following state of affairs:

** _____*

** _____*

** _____*

14. Death occurs within 3 to 4 days for most mammals post irradiation when exposed to large enough radiation fields to deposit doses within the gastrointestinal syndrome range.

a. Death is due to:

- _____*
- _____*
- _____*

b. The irradiated animal dies of _____

5. The Cerebrovascular Syndrome

1. The mean survival time post irradiation for a dose large enough to bring on the cerebrovascular syndrome is dose dependent.

2. The threshold for this syndrome for most species is in excess of 5000 rad.

3. The signs and syndromes elicited are characteristic of damage to the central nervous syndrome.

4. Manifestations of the Cerebrovascular syndrome include:

- a. Periods of agitation alternating with remarkably apathetic behavior.
- b. _____
- c. upsets of equilibrium
- d. loss of coordination of muscular movement (ataxia)
- e. diarrhea
- f. vomiting
- g. tetanic spasms of the muscle of the back
- h. _____

- i. seizures
- j. prostration
- k. _____
- l. death
- m. salivation (occasionally)
- n. diarrhea (occasionally)
- o. oscillatory movement of the eyes - nystagmus (occasionally)

Histologic and Inflammatory Changes Observed During The Cerebrovascular Syndrome

A. Blood cells filter into the meninges.

1. In particular, one may observe the following formed elements within the meninges:
 - a. Granulocytes
 - b. mononuclear types
 - c. macrophages

2. Along with the granulocytic infiltration, inflammation of the meninges is observed initially, increasing to a maximum, and then decreasing slightly

B. Inflammation of blood vessels and lymph tissues (vasculitis) may be observed a few hours after a high radiation dose.

1. Veins and arteries of all sizes undergo changes which involve infiltration of granulocyte in foci about the vessel.

2. Damage to blood vessels leads to changes in capillary permeability.

a. This results in leakage into the brain.

i. It is a question if the damages observed are critical to the death of the exposed individual or are incidental.

b. This leakage into the brain, edema, is responsible for some local cell damage.

c. There is an increased water content of the brain in those whose heads have been irradiated. This is reflected in changes in specific activity.

C. One observes profound alterations in the cerebrum:

1. The cerebellum, brain stem and spinal cord seem less involved.

2. Alterations appear first in gray matter, ultimately white matter becomes seriously involved.

D. The choroid plexuses are quickly affected by the radiation.

1. edema and infiltration of leukocytes occur soon after irradiation.

a. This is probably associated with the creation of micro-hemorrhages and necrosis.

E. The Immediate Cause of Death

1. The exact cause of death from the cerebrovascular syndrome is not known for certain.

2. The Cerebrovascular Syndrome is truly a total body syndrome.

a. Segregated head doses without whole body exposures in the cerebrovascular syndrome range do not produce lethality.

3. Death is presumed to result from events taking place within the skull:

a. swollen meninges

b. damaged blood vessels

c. blood leakage in the brain, edema and intracranial pressure

d. obvious damage to sections of the brain

4. Although many cells have received lethal doses of radiation there is no evidence of necrotic areas.

a. Although neurons may have been lethally irradiated there does not appear to have been a loss of function prior to death, this does not therefore cause death.

Effects on Developing Embryos

A. The embryo probably represents the most radiosensitive stage in the life of any organism.

1. This is true for several reasons:

a. Many of the cells in the embryo are differentiating

i. According to Bergonie' and Tribondeau differentiating cells are highly radiosensitive.

2. There is a high rate of mitotic activity in the embryo, the embryo system is proliferative.

a. Mitosis is a sensitive time of the cells life cycle.

b. It can be generalized that the organ system undergoing differentiation will acquire great radiosensitivity.

3. The cells of the embryo will have a long ancestral future.

a. They serve as the ancestral cells to vast numbers of cells in the adult.

b. If an embryonic cell is killed, at any time in the development of certain embryos and after certain stages of development of nearly all embryos- the cells for which it would have been an ancestor will not be formed.

i. sometimes another cell can and will take over the functions of the lost cells.

ii. Embryos are usually capable of much greater regeneration than those of adults.

- The loss of individual cells typically does not result in the loss of progeny functions but it will serve as a stress on the embryo.

- This stress is expressed as the observed smaller embryo size.

+ This smaller embryo will appear grossly normal however they will display both cytologic and histologic damage when examined closely.

* Their life span will be shortened.

* Certain behavioral performances will not be on par with their unirradiated peers.

4. There are several teratogenic agents other than ionizing radiation.

a. In most cases the abnormality produced is often more characteristic of and dependent upon the system developing when the embryo-deforming agent is used rather than upon the agent itself.

b. The reactions of the system (damage to the cells in it) will always be expressed in the same way - incomplete or abnormal development of the system.

5. Expected Developmental Abnormalities

a. Irradiation of the developing embryo before it becomes implanted into the uterus usually results in death rather than the production of abnormalities.

- It has been observed in mice that preimplanted cells are very sensitive to radiation exposure. At doses as low as 200 Rad in mice 80% of the preimplanted cells will die.

b. Irradiation of the embryo during organogenesis leads to malformations and to neonatal death (rather than prenatal death).

- Organogenesis occurs in humans between about the 7 to 12 week after fertilization.

For mice and rats the following table reflects the type of teratogenic effect expected if the exposure occurs at different times after fertilization:

Time Post Fertilization	Effect
-------------------------	--------

Mice

day 7 to 8	microphthalmia (tiny eyes) skeletal anomalies
------------	--

day 9 to 10	coloboma (fissure of the eye) spina bifida occulta (a defect in the closure of the spinal canal)
-------------	---

hernia, urogenital anomalies

Rats

day 9, 10, and 11

*anencephaly (the absence of cerebrum and cerebellum)
flat bones in the skull anophthalmia (missing eye or eyes)
hydrocephalus (fluid in and around the brain)*

day 12

*microcephaly (pin head)
(this corresponds to the fourth week in humans)*

- c. During the first third of pregnancy the embryo is the most vulnerable.*
- d. In the second third it is less sensitive.*
- e. In the last third it is relatively resistant.*
- f. in utero exposure at Hiroshima and Nagasaki resulted in the following conditions:*
 - i. mental retardation*
 - ii. less than expected head circumferences*
 - iii. strabismus (an abnormality of the eyes in which the visual axes do not meet at the desired objective point. This is felt to be consequence of in-coordinate action of extrinsic ocular muscles)*
 - iv. Congenital malformations of the hips*
 - v. increased incidence of congenital heart disease*
 - vi. increased incidence of fetal death*

Remember these observations are associated with very large acute exposures. These occurred primarily to survivors between than 1200-meters to 2000-meters to ground zero.

Treatment of Irradiated Organisms

A. Lethality associated with total-body irradiation induced syndromes has been ascribed to cells of all tissues of the body.

B. However, death is primarily from radiation damage to and failure of the cell renewal systems of the hematopoietic and gastrointestinal systems.

C. Therefore, a reasonable course of treatment may be to somehow mitigate the consequences associated with the failure of these two systems.

- a. This assumes that the damaged can and will be eventually regenerated.*
- b. Additionally, it is assumed that both primary and secondary manifestations of acute radiation sickness can be treated.*

D. The Treatment of Secondary Manifestations

a. The secondary manifestations which must be treated if even short-term survival is to be possible include:

- 1. the deficit in granulocytes (granulocytopenia)*
- 2. the deficit of thrombocytes (i.e. platelets, red blood cells) - called thrombocytopenia*
- 3. anemia*
- 4. fluid loss*
- 5. electrolyte imbalance*

E. An organism receiving large doses of radiation is much more susceptible to infection by nearly any kind of bacteria this is correlated to:

- a. The break down in various types of barrier tissues*
- b. The depression of granulocytes*

F. For these reasons replacement therapy, the replacement of lost granulocytes via transfusion, in theory would seem to mitigate the consequences of the bacterial infection following lethal exposure.

a. The actual application of this, however, has produced somewhat disappointing results.

i. This is thought to be associated with the short half-life of mature granulocytes in man, between 6 and 8 hours.

ii. The implication of this short half-life is that if transfusion is going to be useful copious numbers of granulocytes will have to be introduced into the exposed individual's system during the whole period of time granulocyte depression is experienced.

iii. The principle, nevertheless, is valid to modify the course and extent of infection.

G. Treatment of Infection with drugs.

a. Antibiotics may be used during the period of granulocyte depression to help control bacterial infection.

i. They should be administered at the first signs of fever.

ii. Because bacteria rapidly becomes resistant to antibiotics it is not unusual to observe secondary increases in temperature with time.

ii. It is recommended that combinations of bacteria

b. A combination of antibiotics and blood platelets has been used effectively in dogs to prevent death from massive radiation exposures.

c. Antibiotic therapy in general has shown mixed results.

i. In some instances it has been very effective, in other cases it was of limited, or nor observable, benefit.

ii. The principle, however, is valid.

H. Control of Hemorrhage

a. Even if granulocyte and antibiotic therapy is successful in avoiding infection the hazard of hemorrhage due to thrombocytes remains.

b. A treatment to prevent lethal hemorrhage involves platelet transfusion.

i. The difficulty is that platelets rapidly lose the qualities needed in the treatment of radiation exposure.

ii. When repeated transfusions are performed the life of transfused cells decreases and the transfusion becomes less and less effective.

- This is associated with the development of antibodies in both the irradiated and unirradiated host which agglutinate and destroy the transfused cells.

- The platelets of mammals typically have a life of about 5 days.

I. Treatment of Dehydration

a. During the late portions of the gastrointestinal syndrome the gut becomes denuded of cells. This is accompanied by severe fluid loss.

b. This severe water loss must be compensated for if time is to be given to the gut lining to replenish itself.

c. Fluid replacement combined with antibiotic therapy is useful.

i. Dogs which have received large acute doses of radiation have enhanced survival rates and survival times following this treatment if administered slightly before the start of infection.

J. Bone-Marrow Replacement

a. The transfusion of bone-marrow cells to lethally irradiated individuals may confer benefit to irradiated individuals.

- b. The degree of success experienced with bone marrow transplants is associated with the quantity of marrow transplanted.
 - i. The more marrow transplanted the higher and more rapid the success.
- c. The problem is finding an acceptable source of unirradiated marrow. A genetically appropriate donor is necessary.
- d. Autotransplants, using the irradiated individuals own marrow obtained prior to irradiation are expected to be successful.
- e. Chernobyl experiences with bone-marrow transplants were not encouraging

K. In general the treatments of radiation syndrome are treatments of the signs and symptoms.

- a. The goal is to prolong the window of opportunity for regeneration of damaged tissues.
 - i. The damage, nevertheless, has occurred in the individual and despite treatment may often be too extensive to avoid death.
 - ii. With treatment, suffering can be reduced even if the patient has little chance for survival.

