Radiation Safety Information
for Students in Courses given by the Nuclear Physics Group at KTH, Stockholm, Sweden

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The aim of this text is to explain some of the basic quantities and units of interest for radiation safety and to give the reader a basic understanding about how to handle radioactive sources used during the laboratory exercises. The text is limited to discuss only *ionising* radiation, i.e. radiation from nuclear decay (α, β, γ) or X-rays.

Quantities and Units

Below follows a description of some basic quantities and units used when describing the effects of radiation on humans.

The **Activity** (A) of a radioactive source is the number of the nuclear decays in the source per unit time. The SI unit for activity is *Becquerel* (Bq). $1\,Bq = 1$ decay/s. The old unit is *Curie* (Ci). 1 Ci correspond to the activity of one gram of radium. $1\,Ci = 3.7 \cdot 10^{10}\,Bq$.

The **Absorbed Dose** (D) is the absorbed radiation energy per unit mass of material (for example a human body). The SI unit is *Gray* (Gy). $1\,Gy = 1\,J/kg$.

Dose Equivalent (H) (also referred to as *human-equivalent dose* or *radiation-weighted dose*) is used in order to estimate the effect of a certain type of radiation on a biological system. Dose Equivalent is a product of the Absorbed Dose (D) and the radiation weighting factor (W_R) of the radiation type R.

Radiation Type	Energies	W_R
X-ray photons, γ photons, electrons	All energies	1
protons	$> 2\,\mathrm{MeV}$	5
neutrons	$< 10\,\mathrm{keV}$	5
	$10\,\mathrm{keV} - 100\,\mathrm{keV}$	10
	$100\,\mathrm{keV} - 2\,\mathrm{MeV}$	20
	$2\,\mathrm{MeV} - 20\,\mathrm{MeV}$	10
	$> 20\,\mathrm{MeV}$	5
α, heavy ions, fission fragments		20

Table 1: Radiation Weighting Factors (W_R) of for different radiation types.

$H = D \cdot W_R$. If the total dose is an effect of more than one type of radiation, all contributions are added:

$$H = \sum_R D_R \cdot W_R, \tag{1}$$

where D_R is the absorbed dose from a specific radiation type R. The SI Unit of the dose equivalent is Sievert (Sv). The old unit is *roentgen equivalent in man* (rem). $1\,rem = 0.01\,Sv$.

The **Radiation Weighting Factor** (W_R) gives a measure of the biological damage to a human for a particular type of radiation. Calculated values of W_R for various radiation types (and energies) are listed in table 1. We should note that W_R is dimensionless. This means that *Sievert* has the same dimension (J/kg) as *Gray*. Since the unit *Sievert* should not be confused with the unit *Gray*, it might be clearer to speak of *Sievert* (Sv) in terms of "equivalent J / kg".

The *effective human-equivalent dose*, usually referred to as the **Effective Dose** is denoted H_E, and measures the whole-body biological damage due to various forms of radiation exposure of different parts of the body. This

Tissue or Body Part	W_T
Gonads	0.20
Bone Marrow	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Esophagus	0.05
Thyroid	0.05
Skin	0.01
Bone Surface	0.01
Remainder: adrenals, brain, upper large intestine, small intestine, kidney, muscle, pancreas, spleen, thymus, uterus	0.05
Total:	1.00

Table 2: Tissue Weighting Factors (W_T) for various human organs and types of tissue.

effective equivalent dose is given as follows:

$$H_E = \sum_T W_T \cdot H_T, \tag{2}$$

where H_T is the dose equivalent for the tissue or body part T, and W_T is the tissue weighting factor for T. W_T is without dimension, so the unit of H_E is Sievert (Sv), the same as for H_T.

Values of **Tissue Weighting Factor** (W_T) for different organs are listed in table 2.

The dose rate distribution during exposure from a radioactive source depends on the types of ionising radiation emitted from the source and their respective energy release rates in the human body ($\sim$ water). For photons we estimate the dose rate from the photon energy flux and the photon mass energy-absorption coefficient $\frac{\mu_{en}}{\rho}$, see fig. 1.

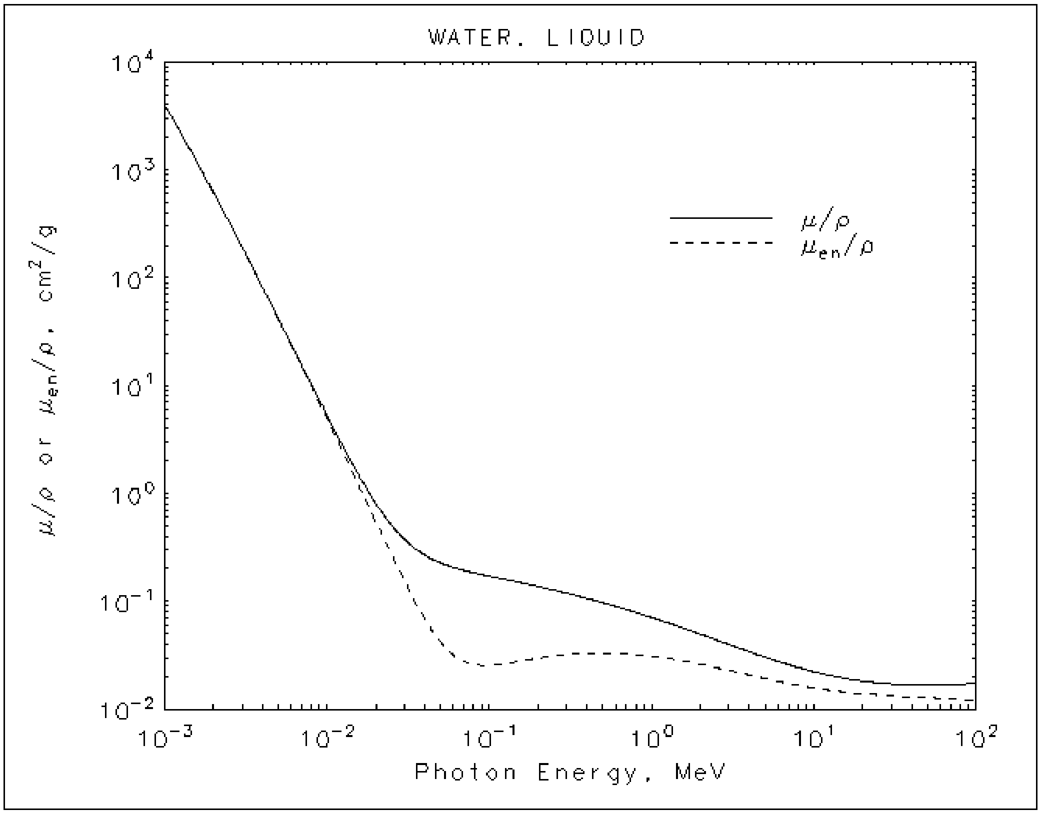

Figure 1: Values of the mass attenuation coefficient, $\frac{\mu}{\rho}$, and the mass energy-absorption coefficient, $\frac{\mu_{en}}{\rho}$, in water as a function of photon energy. The figure is taken from the National Institute of Standards and Technology web site, http://physics.nist.gov/.

Effects of Radiation on the Human Body

The effects of ionising radiation on the human body can be divided into two types; *deterministic effects* and *stochastic effects*.

Deterministic Effects

A deterministic effect *will* appear as a consequence of a certain radiation dose, and will increase if the dose is increased. Deterministic effects will only appear after the absorption of high doses, and will usually show up shortly (within hours or days) after the irradiation. The deterministic effects include nausea, hair loss, damage to the blood and bone marrow, damage to the intestines, and damage to the central nervous system.

The threshold level above which deterministic effects occur lies at 0.1-1 Sv. These first effects include temporary sterility and induced defects on embryos during early pregnancy. At a dose of 1-2 Sv the symptoms include nausea and vomiting (radiation sickness), effects on the blood, and bone marrow damage. At these dose levels, the majority of irradiated persons will recover to normal health within a few weeks.

At higher dose levels, the damage of the blood and bone marrow will be increasingly severe. The dose level at which 50% of the irradiated persons will die within a certain time (usually chosen as 60 days) is called *median Lethal Dose* (LD_{50}) and lies at around 4 Sv. At doses above 5 Sv, damages on the intestines will be considerable, and at even higher doses the central nervous system will be affected. Very few people have survived a full-body dose above 6 Sv.

All of the above assume that the dose in question is absorbed in a short period of time (at a dose rate of 1 Sv/min or more). If the dose is absorbed at a low rate, the body is more capable to recover.

It should be pointed out that the dose levels at which deterministic effects occur are extremely high. A dose of 1 Sv is about 250 times higher than the average dose a person living in Sweden will absorb in one year.

Stochastic Effects

A stochastic effect will only appear with a certain probability, after a certain dose has been absorbed. If the dose is increased, the probability for the effect will increase, but the effect itself will not be more severe. Stochastic effects can show up a long time (several years) after the exposure to radiation. The effects include various types of cancer, and genetic effects.

The stochastic effects are consequences of cell mutations (in contrast to cell death for deterministic effects). Such mutations could induce cancer or, if they appear in gametes, give effects on later generations.

It is a difficult task to find the probabilities that govern the stochastic effects. One reason for this difficulty is that the dose is usually not known with good accuracy. Another problem is that the probabilities involved are small. As a consequence of this, it is often difficult to separate the effects of radiation from the effects of other factors. To illustrate this we use an example:

Consider a person who receives a dose of 10 mSv during an accident in a laboratory. According to modern research on stochastic effects (M. Isaksson, Grundläggande strålningsfysik, Studentlitteratur, 2002), the risk of death in cancer due to radiation is considered to be $5\%/Sv$. In the present case, the risk of death in cancer is $0.05 \cdot 0.01 = 0.05\%$. This number should be compared with the risk, from other factors, of death in cancer, which is around 20% in Sweden.

The problem of stochastic effects of radiation on humans is complex and difficult, and a full description is beyond the scope of this text. One question often under debate, is whether or not there exists a threshold dose level, below which no stochastic effects appear. But even though the problem is difficult, much effort has been made by researchers to get a better understanding of how small doses of ionising radiation affect humans. The recommended dose limits of today are results of many years of research in this field.

Radioactivity in Our Daily Life

To find out if a dose absorbed during work with radioactive material will considerable increase the total absorbed dose, we need to know to what extent naturally occurring radioactivity affects us.

The average effective dose that a person living in Sweden will absorb is close to 4 mSv. Around 45% of this average dose comes from radioactive radon gas in houses. Medical diagnostic procedures and treatments represent around 35%. Other contributions include natural radioactivity in food, cosmic radiation, work with radioactive materials, etc. In fact, all humans are (and have always been) radioactive in themselves, due to natural concentrations of radioactive isotopes (mainly ^{40}K and ^{14}C).

Dose Limits

The Swedish Radiation Protection Authority (SSI) determines (supported by the Swedish Radiation Safety Act (Strålskyddllagen (SFS 1988:220)) the maximum allowed doses from ionising radiation for people living in Sweden. These dose threshold values depend on various circumstances. The sum dose from all human activities regarding ionising radiation to the general public may not exceed:

- 1 mSv per year effective dose
- 15 mSv per year equivalent dose to the eye's lens
- 50 mSv per year equivalent skin dose (averaged per cm^2)

The dose limit for how much the nuclear power plants are allowed to affect the population is 0.1 mSv per person and year. As seen from table 3, a person working with radioactive materials (in nuclear medicine, nuclear power, etc) is allowed to maximum effective dose of 50 mSv during one year, but not more than 100 mSv during any period of five years. These dose limits are also valid for students above 18 years of age who use radiation sources in their education.

The limits for radioactivity from radon in air is (in Sweden) determined by the National Board of Health and Welfare (Socialstyrelsen). A limit of 400 Bq/m^3 is set for older buildings. In new buildings the maximum allowed value is 200 Bq/m^3. A value of 100 Bq/m^3 corresponds approximately to a dose of 2 mSv per year.

For more information (in Swedish) about dose limits, and about the Swedish radioactive environment, see the information at the web page of SSI (Swedish Radiation Protection Authority) at www.ssi.se.

Open and Sealed Sources

The radioactive sources used in the student laboratory can be divided into two types; *sealed sources* and *open sources*. In a sealed source, the radioactive

Personnel type	Quantity	Highest permissible effective dose or equivalent dose (mSv)
Employees and students* above 18 years of age		
	Effective yearly dose	50
	Equivalent yearly dose to the eye's lens	150
	Equivalent yearly skin dose	500
	Equivalent yearly dose to extremities	500
	Effective dose during five consecutive years	100
Students* between 16 and 18 years of age		
	Effective yearly dose	6
	Equivalent yearly dose to the eye's lens	50
	Equivalent yearly skin dose	150
	Equivalent yearly dose to extremities	150

Table 3: Dose limits for persons working with ionising radiation.

* Students and apprentices that use radiation sources for their education.

material is covered with a sealing material, e.g. plastic. If the seal is kept intact, the radioactive material cannot be removed from the source. Only the radiation escaping the sealing material will be measurable.

Open sources have no sealing material. This means that there is a risk of removing small parts of the radioactive material when handling the source. If touched with bare hands, small amounts of the material can stick to them. Depending on the half-life and the activity of the source, this is potentially dangerous, since radioactive material on or in the body can irradiate the body organs for a long time. When handling open sources, adequate safety measures should be taken. One way of reducing the risks is to use protective gloves.

The reason to use open sources is usually that the radiation of interest emitted from the source would be absorbed if a sealing material was present. This is the case for alpha- and fission sources, since alpha particles and fission fragments at typical decay energies have a very short range in typical sealing materials. Gamma sources used for emitting low energy gamma rays can also be open so that the intensity is not lost in a sealing material. Gamma sources with energies above 25 keV are usually sealed.

Safety Measures in the Student Laboratory

All students should follow the rules in the list below.

- If you have any doubts or questions concerning radiation safety, ask the laboratory assistant for help.
- The activity of radioactive sources can vary many orders of magnitude. Make sure that you know the activity of the source you are using.
- It is good practice to calculate the approximate dose that a certain source will give you during the exercise.
- Make sure that you know if the source is open or sealed. Never touch an open source.
- Always try to keep the radiation dose you absorb As Low As Reasonably Achievable (ALARA). This means for example that you should not hold a source in your hand any longer than necessary. Use lead or other materials to shield the source if you can reduce your dose in that way.
- Do not bring food or beverages to the laboratory.

Questions

The following questions should be answered before attending any activity in the nuclear physics student lab.

- What is the approximate (order of magnitude) dose a student will absorb during a laboratory exercise of five hours. Make reasonable assumptions about the average distance to the radioactive source, etc. Calculate for the following two cases:
  - A sealed (1 mm plastic shield) 10 μCi ^{137}Cs source. ^{137}Cs emits gamma rays with photon energies of 662 keV and a branching ratio of 85%.
  - An open 1 μCi alpha source emitting 5 MeV alpha particles inside a vacuum container made of 5mm steel.

Compare your results with the dose rate from the background radiation you are exposed to in your daily life.