Q1: (30 points)
(a) Please explain what is the Bragg-Gray principle? Please write down the equation, explain what each individual term in the equation stands for.
(b) Please explain what is Kerma dose? What is the difference between Kerma dose and the standard dose (energy deposition per unit mass)?
(c) What is specific gamma-ray constant? Please use the data shown in the table below to derive the specific gamma-ray constant for I-131 (Note that it takes 34 J of energy deposited in air to generate 1 C of ionization charge, and the density of air is 1.225 kg/m³).

<table>
<thead>
<tr>
<th>Quantum Energy, MeV</th>
<th>Photons per Transformation</th>
<th>Energy Absorption Coefficient for Air, m⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.723</td>
<td>0.016</td>
<td>$3.8 \times 10^{-3}$</td>
</tr>
<tr>
<td>0.637</td>
<td>0.069</td>
<td>$3.9 \times 10^{-3}$</td>
</tr>
<tr>
<td>0.503</td>
<td>0.003</td>
<td>$3.8 \times 10^{-3}$</td>
</tr>
<tr>
<td>0.326</td>
<td>0.002</td>
<td>$3.8 \times 10^{-3}$</td>
</tr>
<tr>
<td>0.177</td>
<td>0.002</td>
<td>$3.4 \times 10^{-3}$</td>
</tr>
<tr>
<td>0.365</td>
<td>0.853</td>
<td>$3.8 \times 10^{-3}$</td>
</tr>
<tr>
<td>0.284</td>
<td>0.051</td>
<td>$3.7 \times 10^{-3}$</td>
</tr>
<tr>
<td>0.080</td>
<td>0.051</td>
<td>$3.2 \times 10^{-3}$</td>
</tr>
<tr>
<td>0.164</td>
<td>0.006</td>
<td>$3.3 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Solution:
Part (a)
Considering a gas cavity is surrounded by a wall medium, where
- the dimension of the gas volume is small compared to the range of the secondary charged particles,
- the wall thickness > maximum range of secondary charged particles,
- the wall thickness is not great enough to significantly attenuate the incident radiation, and
- the wall and gas materials have similar atomic compositions.

In this case, we consider a form of electronic equilibrium is established between the wall and gas volume. Then the energy absorbed per unit mass of the wall, $\frac{dE_m}{dM_m}$, is related to the energy absorbed per unit mass of gas, $\frac{dE_g}{dM_g}$, by

$$\frac{dE_m}{dM_m} = \frac{S_m}{S_g} \times \frac{dE_g}{dM_g}$$

where $S_m$ is the main mass stopping power of the wall medium, and $S_g$ is the mass stopping power of the gas to the secondary electrons.
Part (b)

KERMA stands for “Kinetic Energy Released per Unit Mass”. When a volume is irradiated by a given form of radiation, the KERMA dose accounts for the initial kinetic energy per unit mass carried by the “primary” ionizing particles (including the photoelectrons, positron-electron pairs, recoil electrons, and the scattered nuclei in case of fast neutrons) produced by the interaction of incident radiation per unit mass of the interacting medium.

By comparison, the regular radiation dose is calculated by the total energy absorbed in a unit mass.

Part (c)

Specific Gamma Ray Constant ($\Gamma$): The gamma ray exposure rate from a point source of a unit activity at a unit distance. It is given in unit of coulombs per kilogram per hour at 1m from a 1 MBq point source.

If all gamma rays are considered, the specific gamma-ray constant for $^{131}\text{I}$ can be evaluated using the following equation,

$$\Gamma = 1.043 \times 10^{-6} \sum_i f_i \times E_i \times \mu_i \frac{(C/kg) \ m^2}{MBq \cdot h} = 1.540 \times 10^{-9} \frac{(C/kg) \ h}{MBq \ at \ 1 \ m}$$

where $f_i$ is the fraction of the transformation that yields a photon whose energy is $E_i$, and $\mu_i$ is the linear energy absorption coefficient of the $i$'th photon in air.
Question 2: A solution of P-32 is spilled and contaminates a large surface to an aerial concentration of 37Bq/cm². What is the estimated beta-ray-contact dose rate to the skin, and what is the dose rate at the height of 1 m above the contaminated area?

Note:
1. For P-32, the emitted beta rays carry a maximum energy of $E_{\text{max}}=1.71$ MeV, and an average energy of $E_{\text{average}}=0.7$ MeV.
2. The mass attenuation coefficients of air and tissue for the beta-rays are $\mu_{\text{air}} = 7.78 \text{ cm}^2/\text{g}$, and $\mu_{\text{tissue}} = 9.18 \text{ cm}^2/\text{g}$.
3. The density of air is $1.225 \text{ kg/m}^3$.
4. The density thickness of dead layer of the skin is $0.007 \text{ g/cm}^2$.

Solution:

For $^{32}\text{P}$:

$E_m = 1.71$ MeV \hspace{1cm} $E = 0.7$ MeV.

The beta absorption coefficients in air and in tissue are calculated by substituting 1.71 for the value of $E_m$ in Eqs. (6.20) and (6.21):

$$\mu_{\text{p,a}} = 16(1.71 - 0.036)^{-1.14} \frac{\text{cm}^2}{\text{g}} = 7.78 \frac{\text{cm}^2}{\text{g}}$$

$$\mu_{\text{p,t}} = 18.6(1.71 - 0.036)^{-1.37} \frac{\text{cm}^2}{\text{g}} = 9.18 \frac{\text{cm}^2}{\text{g}}$$

and the dose rate to the skin in contact with the contaminated area is calculated with Eq. (6.26):

$$\dot{D}_b \text{ Gy/h} = \frac{3.6 \times 10^{-10} \times C_a \times E}{\text{cm}^2/\text{h} \times \mu_{\text{p,t}} \text{ cm}^2/\text{g}} \times e^{-0.007 \frac{\text{g}}{\text{cm}^2} \times \mu_{\text{p,t}} \text{ cm}^2/\text{g}}$$

$$= \frac{3.6 \times 10^{-10} \times 37 \times 0.7 \times 9.18}{0.001} \times e^{-0.007 \times 9.18} = 8 \times 10^{-5} \text{ Gy/h} = 0.08 \text{ mGy/h}.$$ 

The dose rate to the skin, at a height of 1 m above the contaminated surface, is calculated with Eq. (6.31):

$$\dot{D}_b = 3.6 \times 10^{-4} \times C_a \times E \times e^{-\mu_{\text{p,t}} \text{ cm}^2/\text{g}} \times e^{-\mu_{\text{p,t}} \times 0.007} \times \mu_{\text{p,t}} \frac{\text{mGy}}{\text{h}}$$

$$= 3.6 \times 10^{-4} \times 37 \times 0.7 \times e^{-7.78 \times 0.129} \times e^{-9.18 \times 0.007} \times 9.18 = 2.9 \times 10^{-2} \text{ mGy/h}.$$
Question 3: Calculate the dose rate to the skin of a person immersed in a large cloud of Kr-85 at a concentration of 37 kBq/m³.

Note:
1. Each Kr-85 decay emits a single beta ray with maximum energy 0.672 MeV and an average energy of 0.246 MeV.
2. The tissue absorption coefficient for the beta rays is $\mu_t = 34.6$ cm²/g.
3. The density thickness of the dead layer (tissue equivalent) of the skin is $0.007 \frac{g}{cm^2}$.

Solution:

First, we could calculate the dose rate, $\dot{D}_{int}$, in a small volume of air submersed inside a radioactively contaminated by beta emitters of a concentration of $C$ (Bq/m³) using the following equation:

$$\dot{D}_{int} \text{ mGy/h} = \frac{C \times \frac{Bq}{m^3} \times \frac{1}{Bq} \times \frac{1}{s} \times \frac{MeV}{t} \times \frac{1}{MeV} \times \frac{1}{s} \times \frac{1}{h} \times \frac{1}{1.293 \frac{kg}{m^3} \times \frac{1}{kg} \times \frac{1}{Gy} \times \frac{1}{10^3 \text{mGy}}}}{10^{-13} \times 3.6 \times 10^{13}}$$

Then the dose rate to the skin, $\dot{D}_b$, of a person submersed in a radioactive cloud containing beta emitters of the same concentration is given by

$$\dot{D}_b = 0.5 \times 1.1 \times \dot{D}_{int} \text{ (air)} \times e^{-\mu_t \times 0.007} = 1.8 \times 10^{-3} \text{ mGy/h (0.18 mrad/h)}.$$
Question 4: What is the absorbed dose rate of a 70-kg person from a whole-body exposure to a mean thermal neutron flux of 1000 neutrons per cm$^2$ per second? (30 points)

Solution:
The dose rate due to the (n,p) reaction is calculated from the following equation,

$$\dot{D}_{np} = \frac{\phi N_N \sigma_N Q}{1 \text{ J/kg Gy}} \times 1.6 \times 10^{-13} \text{ J/MeV}$$

where
- $\phi$ = thermal flux, neutrons per cm$^2$ per second,
- $N_N$ = number of nitrogen atoms per kg tissue, $1.49 \times 10^{24}$,
- $\sigma_N$ = absorption cross section for nitrogen, $1.75 \times 10^{-24} \text{ cm}^2$,
- $Q$ = energy released by the reaction = 0.63 MeV.

So

$$\dot{D}_n = 1 \times 10^3 \times 1.49 \times 10^{24} \times 1.75 \times 10^{-24} \times 0.63 \times 1.6 \times 10^{-13} = 2.628 \times 10^{-10} \text{ Gy/s}$$

For the dose rate due to the gamma rays from the (n,$\gamma$) reaction, the apparent activity of the body can be given by

$$A = \phi N_H \sigma_H \frac{\text{Bq}}{\text{kg}}$$

where
- $\phi$ = thermal flux, neutrons per cm$^2$ per second,
- $N_H$ = number of hydrogen atoms per kg tissue = $5.98 \times 10^{25}$,
- $\sigma_H$ = absorption cross section for hydrogen = $0.33 \times 10^{-24} \text{ cm}^2$

which gives

$$A = 10^3 \text{ cm}^{-2} \cdot \text{s}^{-1} \times 5.98 \times 10^{25} \text{ atoms/kg} \times 3.3 \times 10^{-25} \text{ cm}^{-2}/\text{atom} \times 1.973 \times 10^4 \text{ Bq/kg}.$$  

Consider the apparent gamma activity is uniformly distributed through the whole body, the dose rate to the whole body is given by

$$\dot{D}_H = A \cdot E_{\gamma} \cdot \phi = 1.973 \times 10^4 \text{ Bq/kg} \times 2.23 \text{MeV/decay} \times 1.6 \times 10^{-13} \text{ J/MeV} \times 0.278 = 1.96 \times 10^{-9} \text{ Gy/s}$$

The total dose rate would therefore be $2.2 \times 10^{-9} \text{ Gy/s}$.