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Specific properties of a model of thoron and its decay products in indoor atmospheres

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Abstract. Whereas several models of indoor concentrations of radon and its decay products exist, models for the occurrence and spatial distribution of thoron (^{220}Rn) and its decay products are lacking. This study highlights the specific properties of the thoron decay chain and presents their consequences for a thoron model. The short half-life of thoron results in an inhomogeneous spatial distribution, which is determined by diffusive and advective transport. The long half-life of the decay product ^{212}Pb accounts for a strong influence of air exchange on its overall concentration as well as on its unattached fraction. It could further be predicted that also the unattached part of ^{212}Pb is distributed inhomogeneously. The theoretical structure of a thoron model, which can neglect the most short-lived decay products but must account for the influence of air exchange in a stronger way than it is the case for radon, results from these considerations.

Key words: thoron • ^{220}Rn • radon • indoor model • decay products • air exchange • spatial distribution

Introduction

The radioactive noble gas radon is well known as a health risk. Most previous studies focused on the isotope ^{222}Rn (afterward called radon), while the occurrence of the isotope ^{220}Rn (thoron) was thought to be negligible because of its short half-life of 55.6 s. Therefore, thoron was examined only rarely or as a byproduct of radon measurements. Yet, recent measurement campaigns showed increased thoron concentrations in traditional Chinese cave-dwellings which are dug into the loamy soil of the Central-Chinese Loess Plateau [18, 21]. Its contribution to the inhalation dose is significant there. Thus, the need for a model which describes the occurrence of thoron and its decay products indoors has arisen.

In the 1970s, Jacobi developed a compartment model for the prediction of the concentrations of radon and its decay products in mines, which was enhanced and adapted to indoor atmospheres by several contributors [6, 8, 14]. Because of its general approach, it can be applied also to thoron. However, the decay chain of thoron features some specific properties which necessitate various differences between a compartment model of thoron and its decay products and the noted radon models. These properties as well as the resulting consequences will be discussed in the following to give advice how existing radon models can be adapted to the thoron decay chain and to highlight the requisites of upcoming thoron models.

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Properties of thoron and its decay products

Thoron is a nuclide of the thorium decay chain, which originates from the primordial ^{232}Th. It is subject to alpha-decay with a half-life of 55.6 s. Because of its short half-life it cannot penetrate thick diffusion barriers such as the foundations of houses, but some kinds of building material as loam and granite are known as sources of indoor thoron [2, 12].

The decay products of thoron are alpha- and beta--emitting nuclides with half-lives between 300 ns and 10.6 h (Table 1). The half-lives and decay modes of the nuclides result in the following differences between the decay chains of thoron and radon:

- The half-life of thoron is short compared to macroscopic transport processes of indoor air. A possible consequence is an inhomogeneous spatial distribution as it is described in the literature [13, 21]. In contrast, the long half-life of radon of 3.8 d usually yields homogeneous distributions.
- The half-lives of the longest-lived thoron decay products (^{212}Pb: 10.6 h, ^{212}Bi: 1.01 h) are long compared to the half-life of the mother nuclide. The dominant decay products of radon (^{214}Pb: 26.8 min, ^{214}Bi: 19.9 min) are short-lived in comparison to radon.
- The half-life of ^{212}Pb is long in comparison to prevailing characteristic times of indoor air exchange (about 3 h on average during the heating season, 10 h at most [11], during the summer even less).
- The sum of the half-lives of all nuclides of the thoron decay chain is 11.7 h. The respective value of the radon decay chain until the long-lived ^{210}Pb is 92 h, thus almost 8 times the value of thoron.
- The dominant decay products of thoron feature half-lives which are different by more than one order of magnitude. The half-lives of the dominant decay products of radon are different by less than a factor of 1.4.
- ^{216}Po is too short-lived to be detected in measurements. As alpha-spectrometry is the prevalent measurement technique for radon and thoron decay products, only the concentrations of ^{212}Bi and the immediately following ^{212}Po, which is always in equilibrium with ^{212}Bi, can be measured. Thus, concentrations of thoron decay products can be measured only at one point in the decay chain. In the radon decay chain, such measurements are possible at ^{218}Po as the first and ^{214}Po as the last short-lived decay product, making it possible also to assess the concentrations of intermediate nuclides by interpolation.

Like those of radon, airborne thoron decay products can occur in two size modes: Water molecules cluster around single atoms of a nuclide and form the so-called unattached decay product, which features a diameter in the range of a few atoms (typically 0.3–4 nm [17]). Unattached decay products collide with airborne aerosol particles and may stick to their surface. The aerodynamic properties of such so-called attached decay products are determined by the size and mass of the aerosol particles; depending on their source and fate they may vary strongly. Haninger has found attached radon decay products with diameters in the range from 20 to 3000 nm [5]. As the probability and place of deposition in the respiratory tract depends on the size, unattached and attached decay products entail different dose contributions and must, therefore, be treated separately by a model. A simple quantity describing the relative occurrence of decay products in both states is the unattached fraction f_P, which is the ratio of the concentration of unattached to that of all decay products:

$$f_P = \frac{c_{unatt}}{c_{tot}} = \frac{c_{unatt}}{c_{unatt} + c_{att}} \quad (1)$$

Because of its great relative biological effectiveness, the alpha-particle emission from the thoron decay products is the major contribution to the inhalation dose from the thoron decay chain. Therefore, the total energy of the emitted alpha particles is a suitable measure of the exposure of people to thoron. As with radon, the commonly used quantity is the potential alpha energy PAE, which is the sum of the energies of the alpha particles which are emitted at the decay of the respective nuclide and its decay products until the stable end nuclide. The PAE of the thoron decay products are shown in Table 1.

^{212}Pb with its long half-life gives the dominant contribution to the PAE per activity of the decay chain. The only other significant contribution is from ^{212}Bi, whereas the contributions of the other nuclides are negligible. In total, the PAE and thus approximately also the resulting dose from a specific activity of thoron decay products is about 14 times the PAE and the resulting dose from the same activity of radon decay products.

Structure of the model

Actually, a compartment model of thoron and its decay products should feature the thoron source (i.e. thoron exhalation from the building material) as the first com-

Table 1. Decay data of the nuclides of the thoron decay chain [3]

Nuclide	Decay constant (s^{-1})	Decay mode	Energy of alpha particle (pJ)	PAE per atom (pJ)	PAE/activity (nJ/Bq)	Weighting factor for total PAE of decay chain
^{220}Rn	1.25×10^{-2}	Alpha	1.01	3.34	0.27	–
^{216}Po	4.78	Alpha	1.08	2.33	4.9×10^{-4}	6.5×10^{-6}
^{212}Pb	1.82×10^{-5}	Beta	–	1.25	69.1	0.913
^{212}Bi	1.91×10^{-4}	Alpha (36%) Beta (64%)	0.97	1.25	6.56	0.087
^{212}Po	3.79×10^{-3}	Alpha	1.41	1.41	6.1×10^{-10}	8.1×10^{-12}
^{208}Tl	2.32×10^{3}	Beta	–	0	0	0
Total					75.6	

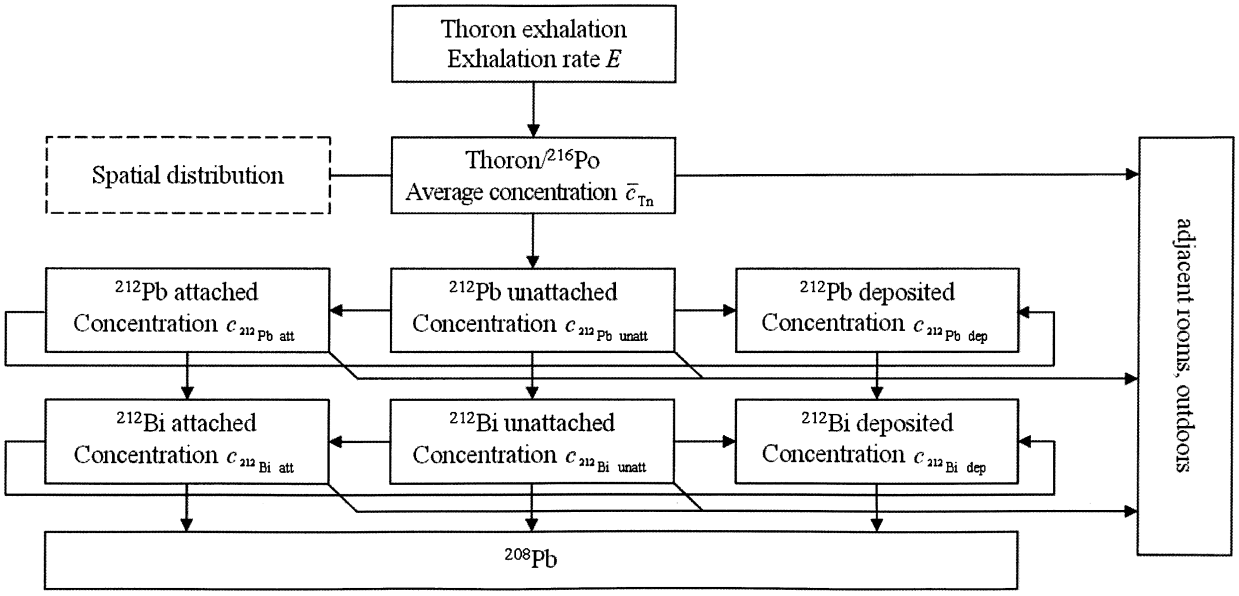

Fig. 1. Structure of a compartment model of the concentrations of thoron and its decay products.

partment, then thoron, and then the individual decay products in the three states unattached, attached, and deposited onto surfaces until the stable nuclide ^{208}Pb. Further compartments should represent the concentrations of the nuclides in adjacent rooms or the outdoor atmosphere, which are connected to the room itself by air exchange and thus can act as sources and sinks of the nuclides. Transfers are possible by radioactive decay, attachment of unattached decay products to aerosol particles, deposition of unattached and attached decay products onto surfaces, detachment of attached decay products as a consequence of the recoil sustained at alpha decay, and air exchange.

Several simplifications, however, are possible even without detailed examination of the involved processes: Because of their short half-lives, ^{216}Po [7] and ^{212}Po are not subject to atmospheric interaction. Therefore, they are in equilibrium with their mother nuclides thoron and ^{212}Bi, respectively, and can be described by their concentrations. Furthermore, ^{216}Po only occurs in the unattached mode. Their contributions to the inhalation dose as well as that from ^{208}Tl are negligible because of their small PAE per activity. Thus, a model focused on the exposure of people can disregard these nuclides (Fig. 1). Because of the missing possibility to resolve the individual decay products in measurements, these simplifications are desirable.

Activity and spatial distribution of thoron and ^{216}Po

After exhalation from the building material, thoron is subject to indoor atmospheric transport processes. Without advective air movement, the only process which acts upon it is diffusion, which is described by the diffusion law:

$$\frac{\partial c_{\mathrm{Tn}}}{\partial t} = D \cdot \frac{\partial^2 c_{\mathrm{Tn}}}{\partial d^2} \tag{2}$$

Boundary condition for the solution of this differential equation is a homogeneous concentration inside the building material ($d < 0$) and a thoron-free indoor air at $t = 0$. Then, the solution of the diffusion law is given by the Gaussian error function erf:

$$c_{\mathrm{Tn}}(d) = c_0 \left(1 - \mathrm{erf}\left(\frac{d}{2\sqrt{Dt}}\right)\right) \tag{3}$$

where: $\mathrm{erf}(x) = (2/\sqrt{\pi}) \int_0^x \exp(-z^2)\mathrm{d}z$ and c_0 as the thoron concentration at $d = 0$.

As the lifetime of thoron is finite, it is not distributed homogeneously in indoor air. Where:

$$L = \sqrt{2D\tau_{\mathrm{Tn}}} \quad [4] \tag{4}$$

the spatial distribution in equilibrium of diffusion and decay is given by:

$$c_{\mathrm{Tn}}(d) = c_0 \left(1 - \mathrm{erf}\left(\frac{d}{\sqrt{2}L}\right)\right) \tag{5}$$

The diffusion coefficient D of radon in air was found as 0.12 cm^2/s by Underhill [20]. Because of similar thermodynamic properties, this value can also be used for thoron and yields a diffusion length of thoron in air of 4.4 cm (Fig. 2).

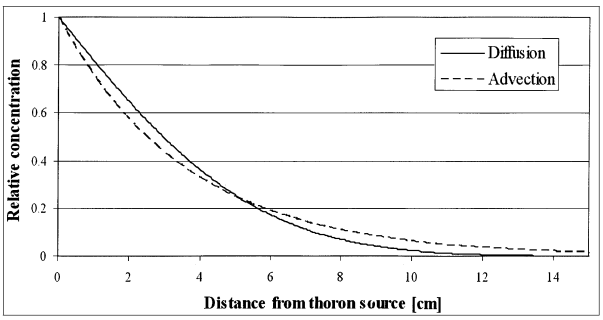

Fig. 2. Spatial distribution of thoron with transport by diffusion and by advection as calculated by Eqs. (6) and (9). The diffusion length L is assumed as 4.4 cm, the applied transport velocity $v = 0.05$ cm/s was chosen such that the total activities in both cases are equal.

If air movement occurs in the room, thoron can also be transported by advection. If a constant air velocity $v = \mathrm{d}d/\mathrm{d}t$ is assumed, the law of radioactive decay

$$\mathrm{d}c_{\mathrm{Tn}} = -\lambda_{\mathrm{Tn}} c_{\mathrm{Tn}} \mathrm{d}t \tag{6}$$

yields an exponential function as the spatial distribution:

$$\mathrm{d}c_{\mathrm{Tn}} = -\frac{\lambda_{\mathrm{Tn}} c_{\mathrm{Tn}}}{v} \mathrm{d}d \tag{7}$$

If the thoron concentration at $d = 0$ is c_0, the differential equation can be solved as

$$c_{\mathrm{Tn}}(d) = c_0 \cdot \exp\left(-\frac{\lambda_{\mathrm{Tn}} d}{v}\right) \tag{8}$$ (Fig. 2).

In both cases, the constant c_0 can be calculated from the exhalation of thoron from the building material, which can easily be measured in the laboratory [19]. Without air exchange, which is negligible in most instances due to the short half-life of thoron, the total activity A_{Tn} of thoron in the room depends on the exhalation rate:

$$A_{\mathrm{Tn}} = \frac{E \cdot S_{\mathrm{Tn}}}{\lambda_{\mathrm{Tn}}} \tag{9}$$

The total thoron activity is also equal to the integral of the spatial distribution of the thoron concentration:

$$A_{\mathrm{Tn}} = S_{\mathrm{Tn}} \cdot \int_{d=0}^{\infty} c_{\mathrm{Tn}}(d) \mathrm{d}d \tag{10}$$

After integration of the thoron concentration, the synopsis of Eqs. (9) and (10) yields for diffusive transport:

$$c_0 = \sqrt{\frac{\pi}{2}} \frac{E}{\lambda_{\mathrm{Tn}} L} \tag{11}$$

and for advective transport:

$$c_0 = E / v \tag{12}$$

Air exchange plays a role as a sink or source of thoron only if the air exchange rate is in the same order of magnitude as the decay constant of thoron, which is the case with air exchange rate greater than about 10 h^{-1}. Then, the thoron activity in the room can be written as:

$$A_{\mathrm{Tn}} = \frac{E \cdot S_{\mathrm{Tn}} + \mathrm{aer} \cdot c_{\mathrm{Tn\ aer}} \cdot V}{\lambda_{\mathrm{Tn}} + \mathrm{aer}} \tag{13}$$

With its short half-life of 150 ms, ^{216}Po is always close to equilibrium with thoron [7]; thus it features the same spatial distribution as its mother nuclide. As it occurs with high concentrations in short distance to the thoron exhaling building material, deposition onto the building material might be a significant sink of ^{216}Po. Measurements of the spatial distribution of thoron and of the deposition velocity of ^{216}Po are needed to assess the influence of the deposition.

Concentrations of ^{212}Pb and ^{212}Bi

Source of ^{212}Pb is the decay of ^{216}Po. With its long half-life of 10.6 h, ^{212}Pb can disperse homogeneously in a room. Therefore, its concentration does not depend on the local but on the average concentration of its inhomogeneously spread mother nuclide, which is dominated by high concentrations in a small volume close to the thoron exhaling building material. Another source of ^{212}Pb can be the air exchange with a room which contains a thoron source; this can yield significant concentrations of ^{212}Pb even if there is no thoron source and thus no thoron in the room itself. Sinks of ^{212}Pb are radioactive decay, air exchange, and deposition onto surfaces. Thus, the concentration $c_{212\mathrm{Pb}}$ of ^{212}Pb (Fig. 3) is given by

$$c_{^{212}\mathrm{Pb}} = \frac{\lambda_{^{212}\mathrm{Pb}} \cdot \overline{c}_{\mathrm{Tn}} + \mathrm{aer} \cdot c_{^{212}\mathrm{Pb\ aer}}}{\lambda_{^{212}\mathrm{Pb}} + \mathrm{aer} + \delta} \tag{14}$$

The deposition rate δ can be calculated from the deposition velocity v_{dep} and the surface-to-volume-ratio S/V of the room: $\delta = v_{\mathrm{dep}} \cdot S/V$.

Similarly, the concentration $c_{212\mathrm{Bi}}$ of ^{212}Bi is

$$c_{^{212}\mathrm{Bi}} = \frac{\lambda_{^{212}\mathrm{Bi}} \cdot c_{^{212}\mathrm{Pb}} + \mathrm{aer} \cdot c_{^{212}\mathrm{Bi\ aer}}}{\lambda_{^{212}\mathrm{Bi}} + \mathrm{aer} + \delta} \tag{15}$$

Because of the half-lives of ^{212}Pb and ^{212}Bi, which are longer than those of ^{214}Pb and ^{214}Bi from the radon decay chain, radioactive decay plays a smaller role, whereas air exchange and deposition are more important sinks for thoron decay products than for radon decay products. Especially, the air exchange with characteristic times in the range of several 10 minutes to a few hours can influence ^{212}Pb concentrations much.

In the characterization of radon atmospheres, an important quantity is the equilibrium factor F_{Rn}, which is the ratio of the concentrations of the radon decay products to the concentration of radon itself:

$$F_{\mathrm{Rn}} = \frac{\mathrm{EEC}_{\mathrm{Rn}}}{c_{\mathrm{Rn}}} \tag{16}$$

F_{Rn} lies within a range between 0.2 and 0.8 for most indoor atmospheres [14]. A value of 0.4 is often used

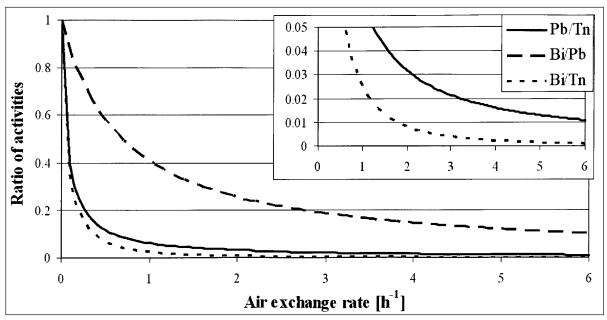

Fig. 3. Ratio of the activities of ^{212}Pb to thoron, ^{212}Bi to ^{212}Pb, and ^{212}Bi to thoron as a function of the air exchange rate according to Eqs. (15) and (16). Deposition is disregarded. Small diagram: enlarged view.

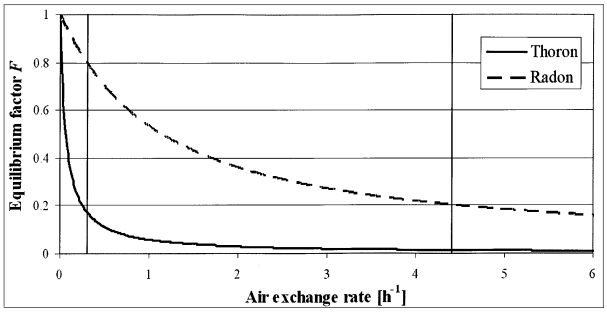

Fig. 4. Calculated equilibrium factors F of the decay chains of thoron and radon as a function of the air exchange rate, if the decay product concentrations are zero in adjacent rooms or outdoors. The equilibrium factor of the thoron decay chain covers a much larger range with prevailing air exchange rates, thus making its assessment more difficult.

as a suitable average for the assessment of radon decay product concentrations from radon gas measurements. For an adoption of the equilibrium factor to the thoron decay chain, the gas concentration must be replaced by the average gas concentration:

$$F_{\mathrm{Tn}} = \frac{\mathrm{EEC}_{\mathrm{Tn}}}{\bar{c}_{\mathrm{Tn}}} \tag{17}$$

where

$$\mathrm{EEC}_{\mathrm{Tn}} = 0.913 \cdot c_{212\mathrm{Pb}} + 0.087 \cdot c_{212\mathrm{Bi}}. \tag{18}$$

Depending on the air exchange, the equilibrium factor can vary within a large range (Fig. 4). At the air exchange rates which result in the mentioned values of F_{Rn}, F_{Tn} features values of 0.013 to 0.18, thus changes by a factor of 14. If there is no thoron source in a room itself but in an adjacent room ($\bar{c}_{\mathrm{Tn}} = 0, c_{212\mathrm{Bi\,aer}} > 0$), the equilibrium factor might even be greater than 1.

Influence of air exchange and deposition on the unattached fraction

Porstendörfer and Reineking found a simple way to specify the unattached fraction f_{P} of radon decay products in close approximation only from its major influence, which is the aerosol concentration [16]. For this purpose, they compared the rate of attachment to aerosol particles with the rate of radioactive decay as the most important further sink:

$$f_{\mathrm{P}\,^{218}\mathrm{Po}} = \frac{\lambda_{^{218}\mathrm{Po}}}{\bar{\beta}Z},$$

$$f_{\mathrm{P}\,^{214}\mathrm{Pb}} = \frac{R \cdot \lambda_{^{218}\mathrm{Pb}}}{\bar{\beta}Z}, \tag{19}$$

$$f_{\mathrm{P}\,^{214}\mathrm{Bi}} = \frac{R \cdot \lambda_{^{218}\mathrm{Pb}} \lambda_{^{218}\mathrm{Bi}}}{\bar{\beta}^2 Z^2}$$

The average attachment coefficient $\bar{\beta}$ is in the range of 0.6 to 1.4 × 10^{-6} $\mathrm{cm^3/s}$ [10, 15]. As the authors admit, this approximation is only valid if the attachment rate $\bar{\beta}Z$ is greater than the rate of radioactive decay, which is true in most atmospheric conditions.

The lifetime of the long-lived dominant thoron decay product ^{212}Pb in a room, however, is usually determined less by its radioactive decay, but by air exchange with the outdoor atmosphere since the characteristic times of air exchange in dwellings are in the range of several 10 minutes to a few hours and thus smaller than the half-life of ^{212}Pb. At least this additional sink must be taken into account, if the approximation by Porstendörfer and Reineking shall be adopted to thoron decay products:

$$f_{\mathrm{P}\,^{212}\mathrm{Pb}} = \frac{\lambda_{^{212}\mathrm{Pb}} + \mathrm{aer}}{\bar{\beta}Z}, \tag{20}$$

$$f_{\mathrm{P}\,^{212}\mathrm{Bi}} = f_{\mathrm{P}\,^{212}\mathrm{Pb}} \frac{(\lambda_{^{212}\mathrm{Bi}} + \mathrm{aer})}{\bar{\beta}Z} = \frac{(\lambda_{^{212}\mathrm{Pb}} + \mathrm{aer})(\lambda_{^{212}\mathrm{Bi}} + \mathrm{aer})}{\bar{\beta}^2 Z^2}$$

(Fig. 5).

Without the constraint of the attachment rate being greater than the decay constant and taking into account also deposition and possible further sinks such as filtration of the air, the concentrations of unattached and attached ^{212}Pb can exactly be specified by solving the differential equations which describe their time-dependence:

$$\frac{\mathrm{d}c_{^{212}\mathrm{Pb\ unatt}}}{\mathrm{d}t} = \lambda_{^{212}\mathrm{Pb}} \cdot \bar{c}_{\mathrm{Tn}} - (\lambda_{^{212}\mathrm{Pb}} + \mathrm{aer} + \bar{\beta}Z + \delta_{\mathrm{unatt}} + \phi) \cdot c_{^{212}\mathrm{Pb\ unatt}} \tag{21}$$

$$\frac{\mathrm{d}c_{^{212}\mathrm{Pb\ att}}}{\mathrm{d}t} = \bar{\beta}Z \cdot c_{^{212}\mathrm{Pb\ unatt}}(t) - (\lambda_{^{212}\mathrm{Pb}} + \mathrm{aer} + \delta_{\mathrm{att}} + \phi) \cdot c_{^{212}\mathrm{Pb\ att}} \tag{22}$$

$$\rightarrow c_{^{212}\mathrm{Pb\ unatt}} = \frac{\lambda_{^{212}\mathrm{Pb}} \cdot \bar{c}_{\mathrm{Tn}}}{\lambda_{^{212}\mathrm{Pb}} + \mathrm{aer} + \bar{\beta}Z + \delta_{\mathrm{unatt}} + \phi} \tag{23}$$

$$c_{^{212}\mathrm{Pb\ att}} = \frac{\bar{\beta}Z \cdot c_{^{212}\mathrm{Pb\ unatt}}}{\lambda_{^{212}\mathrm{Pb}} + \mathrm{aer} + \delta_{\mathrm{att}} + \phi} \tag{24}$$

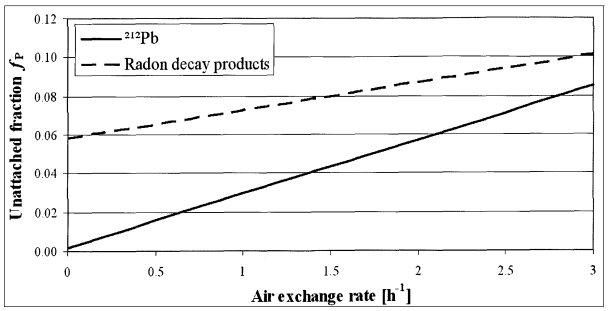

Fig. 5. Unattached fraction f_{P} of ^{212}Pb (Eq. (21)) and of the radon decay products [16] as a function of the air exchange rate. An aerosol concentration Z = 10 000 $\mathrm{cm^{-3}}$ and an attachment coefficient $\bar{\beta}$ = 1.0 × 10^{-6} $\mathrm{cm^3/s}$ are assumed. The unattached fraction of ^{212}Pb is much smaller than that of the radon decay products but increases faster with increasing air exchange rate.

Table 2. Typical values of the quantities which determine the sinks of unattached ^{212}Pb

Quantity	Value (h^{-1})	Comment	Source
λ_{212Pb}	0.065		
δ_{unatt}	≈ 4	Surface/volume ≈ 3 m^{-1}	[1]
aer	< 3–10		[11]
$\bar{\beta}Z$	≈ 15–1000	Z = 4000–250 000 cm^{-3}	[10, 15]

$$f_{P\ ^{212}Pb} = \frac{c_{^{212}Pb\ unatt}}{c_{^{212}Pb\ unatt} + c_{^{212}Pb\ att}} = \frac{c_{^{212}Pb\ unatt}}{c_{^{212}Pb\ unatt} + \frac{\bar{\beta}Z \cdot c_{^{212}Pb\ unatt}}{\lambda_{^{212}Pb} + aer + \delta_{att} + \phi}} = \frac{\lambda_{^{212}Pb} + aer + \delta_{att} + \phi}{\lambda_{^{212}Pb} + aer + \delta_{att} + \phi + \bar{\beta}Z} \quad (25)$$

where ϕ is the rate of possible further sinks which equally affect unattached and attached ^{212}Pb such as filtration of the indoor air. Its value strongly depends on method which is applied to reduce the concentrations of the decay products.

With their longer half-lives, the decay products of thoron have much more time to attach to aerosol particles and therefore occur to a greater extent in the attached state. This is even more distinct with only small influences of the other sinks, particularly with small air exchange rates.

Spatial distribution of unattached ^{212}Pb

Whereas the mean lifetime of ^{212}Pb in a room is governed by radioactive decay, deposition, and the dominating influence of air exchange, also the attachment to aerosol particles must be taken into account for the determination of the mean lifetime $\tau_{^{212}Pb\ unatt}$ of unattached ^{212}Pb:

$$\tau_{^{212}Pb\ unatt} = \frac{1}{\lambda_{^{212}Pb} + \delta_{unatt} + aer + \bar{\beta}Z} \quad (26)$$

Table 2 presents typical values of the quantities occurring in this equation.

The large attachment rate $\bar{\beta}Z$ yields a short mean lifetime of unattached ^{212}Pb of about 4 s to 3 min, depending on the aerosol concentration (250 000 and 4000 cm^{-3}, respectively). In particular with lifetimes of only some seconds, the spatial distribution of unattached ^{212}Pb is close to that of its predecessors ^{216}Po and thoron. Though the deduction of the unattached fraction of ^{212}Pb deduced above is generally true for its average value, large aerosol concentrations and low air mixing result in even smaller concentrations of unattached ^{212}Pb in the middle of the room.

Conclusion

The discussed differences between the decay chains of thoron and of radon and their depicted implications in indoor air result in further potential simplifications of a compartment model for indoor thoron. The unattached fraction of ^{212}Bi is much smaller than that of ^{212}Pb. In combination with the minor contribution of ^{212}Bi to the overall exposure in terms of PAE with a weighing factor of only 0.087, it is well-founded to neglect the unattached fraction of ^{212}Bi. Moreover, in contrast to the radon decay chain, where ^{214}Pb and ^{214}Bi occur as two equally important nuclides with a significant amount in the unattached state, the thoron decay chain features only ^{212}Pb as the single dominant nuclide in the attached state with small contributions of unattached ^{212}Pb and attached ^{212}Bi. Because of the small influence of ^{212}Bi and the similar dose coefficient of the two nuclides [9], it even seems justifiable to take into account only one concentration of unattached and one of attached decay products, each of which is dominated by the respective concentration of ^{212}Pb.

The model also reveals an important consequence on the metrology of exposures to the thoron decay chain. Whereas it is common and in most cases justified to assess exposures to radon and its decay products by the measurement of radon gas and the application of an average equilibrium factor, this method is not applicable to the thoron decay chain: Even an estimation of the thoron equilibrium factor stringently requires knowledge of the air exchange rate and the decay product concentration in adjacent rooms. Furthermore, several measurements of the thoron concentration at different positions in the room are needed to trace its spatial distribution, which yields the significant average thoron concentration. Therefore, the assessment of thoron exposures should be based on measurements of the decay product concentrations.

Abbreviations

A_{Tn} – thoron activity (Bq)
aer – air exchange rate (s^{-1})
$\bar{\beta}$ – average attachment coefficient ($cm^3 \cdot s^{-1}$)
c_{att} – concentration of attached decay products ($Bq \cdot m^{-3}$)
c_i – concentration of nuclide i ($Bq \cdot m^{-3}$)
$c_{Tn\ aer}$ – concentration of thoron in adjacent rooms or the outdoor atmosphere ($Bq \cdot m^{-3}$)
c_{tot} – concentration of unattached and attached decay products together ($Bq \cdot m^{-3}$)
c_{unatt} – concentration of unattached decay products ($Bq \cdot m^{-3}$)
$\bar{c}_{Tn}$ – average thoron concentration ($Bq \cdot m^{-3}$)
d – distance (m)
D – diffusion coefficient ($m^2 \cdot s^{-1}$)
δ_i – deposition rate of unattached, attached and total decay products respectively (s^{-1})
E – exhalation rate ($Bq \cdot m^{-2} \cdot s^{-1}$)
EEC – equilibrium-equivalent concentration ($Bq \cdot m^{-3}$)

erf – Gaussian error function
F_i – equilibrium factor of thoron or radon decay chain
f_P – unattached fraction of decay products
L – diffusion length (m)
λ_i – decay constant of nuclide i (s^{-1})
ϕ – rate of further decay products sinks (s^{-1})
R – recoil factor, probability of detachment sub-sequent to alpha decay
S – area of the surface of the room (m^2)
S_{Tn} – area of thoron-exhaling surface (m^2)
t – time (s)
$\tau_{^{212}Pb\ unatt}$ – mean lifetime of unattached ^{212}Pb in the room (s)
τ_{Tn} – mean lifetime of thoron (s)
v – velocity of advective air transport ($m \cdot s^{-1}$)
v_{dep} – deposition velocity ($m \cdot s^{-1}$)
V – volume of the room (m^3)
Z – aerosol concentration (cm^{-3})

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