Analysis of the possibility of recognizing radioisotopes by measuring the absorbed dose using passive detectors with different atomic numbers

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Motivation and aim of the work

The idea of ionizing irradiation source recognition utilizing measurements of absorbed dose using at least two different detectors with strongly different effective atomic numbers (Z_{eff}) has been around for a long time. However, to date, this approach has not been implemented in practice mainly due to the lack of appropriate detectors made of high atomic number materials.

The aim of this investigation is to analyze and establish a possibility to identify radioisotopes, which could be potentially used in radiation dispersal devices (RDDs), employing the absorbed dose measurements of their γ-radiation with two detectors of different Z_{eff}.

Passive OSL/TSL detectors under consideration

The tissue equivalent BeO ceramics (Z_{eff} = 7.1) has been considered as a "light" detector material, while the single crystalline $YAlO_3$ (YAP) (Z_{eff} = 31.4) or $LuAlO_3$ (LuAP) (Z_{eff} = 61.6) have been chosen as a "heavy" one.

The Mn^{2+}-activated YAP detectors have been investigated experimantally [1,2]. The LuAP is considered as a hypothetical material for dosimetry with very high Z_{eff}, because the (Y-Lu)AlO_3:Mn with partial substitution of Y with Lu demonstrated similar dosimetric properties [3].

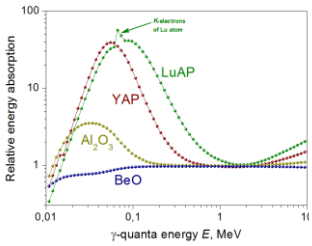

Fig. 1. Dependence of the irradiation absorption (energy deposition) upon radiation energy, obtained by Monte-Carlo simulation in [2] for 1 mm thick detectors.

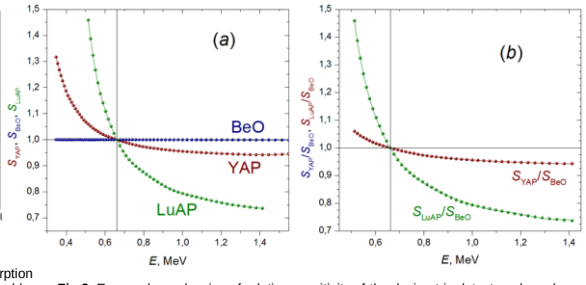

Fig.2. Energy dependencies of relative sensitivity of the dosimetric detectors, based on YAP, LuAP and BeO (a) and their ratios (b) for heavy and light detectors.

Results of the analysis

Isotope	Energy of γ-quanta, MeV	YAP/BeO		LuAP/BeO	
		R	σ_R/ε_D	R	σ_R/ε_D
^{137}Cs	0.662	1	1.414	1	1.414
^{192}Ir	0.82	0.971	1.394	0.862	1.320
^{60}Co	1.25	0.946	1.377	0.751	1.251

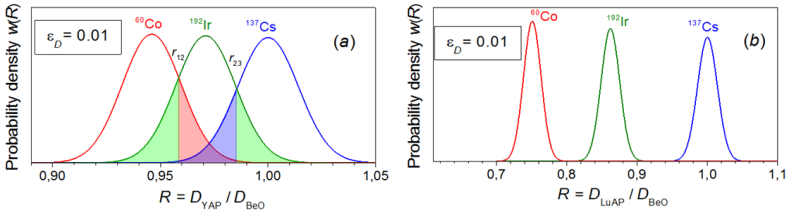

Fig. 3. The probability density distributions of estimated quantities R_i with parameters, presented in Table 2 for the detectors pairs YAP/BeO (a) and LuAP/BeO (b), in the assumption that the absorbed dose measurement possesses the Gaussian distribution of error and has a relative accuracy ε_D = 0.01 (1%).

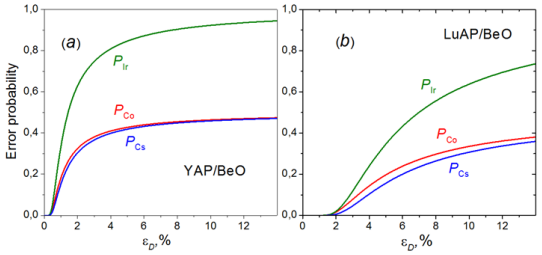

Fig. 4. Dependencies of the radioisotope's identification error probabilities upon the relative error ε_D if the absorbed dose measurement according to the decision-making rule (6) and absorbed dose measurement using detectors pairs YAP/BeO (a) and LuAP/BeO (b).

Table 1. Isotopes can be used in RDD and their main characteristics [4, 5]

No.	Isotope	Decay	Radiation energy, MeV	Radioactive half-life, year	Specific activity, Ci/g
1.	Strontium (Sr-90)	β	0.2 (β)	28	140
2.	Plutonium (Pu-239)	α	5.1 (α)	24 100	0.063
3.	Polonium (Po-210)	α	5.3 (α)	0.4 (138.4 days)	4 500
4.	Radium (Ra-226)	α, β, γ	4.8 (α), 0.0036 (β), 0.0067 (X)	1 602	1.0
5.	Californium (Cf-252)	α, γ	5.9 (α), 0.0012 (X)	2.6	540
6.	Curium (Cm-244)	α, γ	5.8 (α), 0.0017 (X)	18	82
7.	Plutonium (Pu-238)	α, γ	5.5 (α), 0.0018 (X)	87.7	17
8.	Americium (Am-241)	α, γ	5.5 (α), 0.0595 (X)	458	3.5
9.	Cesium (Cs-137)	β, γ	0.19 (β), **0.6617 (γ)**	30	88
10.	Iridium (Ir-192)	β, γ	0.22 (β), **0.82 (γ)**	0.2 (74 days)	9 200
11.	Cobalt (Co-60)	β, γ	0.097 (β), **1.25 (γ)**	5.26	1 100

Main equations used for the analysis:

The measured values of absorbed dose ($D_1 = D_{YAP}$ (or D_{LuAP}) and $D_2 = D_{BeO}$):

$$D_1 = S_1(E) \cdot D,$$
$$D_2 = S_2(E) \cdot D. \quad (1)$$

$$\frac{D_1}{D_2} = \frac{S_1(E)}{S_2(E)}. \quad (2)$$

$$R(E) = \frac{D_1}{D_2}. \quad (3)$$

$$D = \frac{1}{2}\left(\frac{D_1}{S_1(E)} + \frac{D_2}{S_2(E)}\right). \quad (4)$$

$$D = \frac{1}{2}\frac{R(E)}{S_2(E)}\left(D_1 + D_2 R(E)\right). \quad (5)$$

R(Co-60) = R_1 , R(Ir-192) = R_2 and R(Cs-137) = R_3 (see Table 2).

The decision-making rule for isotopes recognition based on the R value:

$$R = \begin{cases} R_1, & \text{if } R < r_{12}, \\ R_2, & \text{if } r_{12} < R < r_{23}, \\ R_3, & \text{if } R > r_{23}, \end{cases} \quad (6)$$

The standard deviation of the indirect measurement of the ratio $R = D_1/D_2$:

$$\sigma_R = \left(\left(\frac{\partial R}{\partial D_1}\right)^2 (\sigma_{D_1})^2 + \left(\frac{\partial R}{\partial D_2}\right)^2 (\sigma_{D_2})^2\right)^{1/2} = \sqrt{(\sigma_{D_1}^2 + R^2\sigma_{D_2}^2)/D_2^2}. \quad (7)$$

In assumption that $\sigma_{D_1} = \sigma_{D_2} = \sigma_D$ and $D_2 \approx D$ (due to very flat dependence of $S_2(E)$) equation (7) can be rewritten in the form:

$$\sigma_R = \sqrt{1 + R^2} \cdot \varepsilon_D, \quad (8)$$

where $\varepsilon_D = \sigma_D/D$ is a relative error of measurement of absorbed dose. The values of σ_R/ε_D calculated for isotopes' energies are presented in Table 2.

Minimal error will occur when the border quantities r_{12} and r_{23} will satisfy equations:

$$w_1(r_{12}) = w_2(r_{12}),$$
$$w_2(r_{23}) = w_3(r_{23}). \quad (9)$$

The error probabilities in identification of isotopes ^{137}Cs, ^{192}Ir and ^{60}Co:

$$P_{Co} = P_R = \frac{1}{2}\operatorname{erfc}\left(\frac{r_{12} - R_1}{\sigma_1\sqrt{2}}\right), \quad (10)$$

$$P_{Ir} = P_G = \frac{1}{2}\left[\operatorname{erfc}\left(\frac{R_2 - r_{12}}{\sigma_2\sqrt{2}}\right) + \operatorname{erfc}\left(\frac{r_{23} - R_2}{\sigma_2\sqrt{2}}\right)\right], \quad (11)$$

$$P_{Cs} = P_B = \frac{1}{2}\operatorname{erfc}\left(\frac{R_3 - r_{23}}{\sigma_3\sqrt{2}}\right), \quad (12)$$

where subscripts R, B, and G correspond to the colors of curves and filling in Figure 3a.

The joint probability of wrong identification as a function of number n of used dosimeters:

$$P_i(n) \sim P_i^n. \quad (13)$$

For instance, using three dosimeters with YAP/BeO pair of detectors reduces the ^{192}Ir isotope identification error probability from 34% to quite an acceptable level of 3.7% at the same accuracy of dose measurement characterized by ε_D = 0.01 (1%).

Summary

♦ The analysis of the possibility of identification of an unknown radiation source was performed in the context of emergency dosimetry by means of measuring the absorbed doses' values using two dosimetric detectors, light BeO and heavy YAP:Mn or LuAP, taking into account the energy dependences of their dosimetric sensitivity, and random errors appearing during measurements.

♦ According to the available sources, the number of radioisotopes which can be used by terrorists in RDDs is very limited, and only three isotopes ^{137}Cs, ^{192}Ir and ^{60}Co are dangerous from the point of view of external γ-irradiation.

♦ The performed analysis shows that the optimal identification of isotopes ^{137}Cs, ^{192}Ir and ^{60}Co using 1 mm thick dosimetric detectors based on YAP and BeO requires unusually high accuracy of measurements of absorbed dose or to use of a pair of detectors which have a bigger difference in observed absorbed doses ratio for the γ-radiation energy range of mentioned isotopes. The possible solution may be the usage of even heavier compounds like LuAP (Z_{eff} = 61.6) or others with higher Z_{eff} instead of YAP.

♦ At the same time, a feasible way to increase the reliability of isotopes' identification is to solve the recognition problem using several identical dosimeters which got irradiated by the same source owing to reducing the joint error probability with an increase of a number of independent identifications.

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Acknowledgements: The work was supported by the NATO SPS MYP program (project G5647), the Polish National Science Centre (project 2018/31/B/ST8/00774), and by the National Research Foundation of Ukraine (grant 2020.02-0373).