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Routine LSC measurements of total alpha and beta activity in Ukraine's drinking water

Mykhailo Buzynnyi

michael.buzinny@gmail.com

State Institution "Marzieiev Institute for Public Health of the National Academy of Medical Sciences of Ukraine"

Liubov Mykhailova

State Institution "Marzieiev Institute for Public Health of the National Academy of Medical Sciences of Ukraine"

Article

Keywords: total alpha, ∑α, total beta, ∑β, 222Rn, liquid scintillation counting, drinking water

Posted Date: November 20th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11623916/v1

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Additional Declarations:
No competing interests reported.

Table 2 is available in the Supplementary Files section.

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Mykhailo Buzynnyi, Liubov Mykhailova

State Institution "Marzieiev Institute for Public Health of the National Academy of Medical Sciences of Ukraine", Kyiv, Ukraine

Corresponding author: Mykhailo Buzynnyi, E-mail: michael.buzinny@gmail.com

Abstract

This article summarizes our experience analyzing total alpha and beta activity in water samples by liquid scintillation counting. We also measured ^{222}Rn in the same samples using an appropriate method. For these analyses, we configured liquid scintillation spectrometers, considering the spectrometer model, scintillation cocktails, and vials. The study presents data from 469 samples collected across twenty regions of Ukraine, covering six water types: underground, wastewater, surface, tap, mine, and bottled. Clients requested the analyses mainly to verify compliance with Ukrainian regulatory standards and, in some cases, to compare results for specific samples. Sample distribution varied by region and water type. The dataset covers the following radioactivity concentration ranges: gross alpha activity (∑α) — 0.005–7.3 Bq/L; gross beta activity (∑β) — 0.02–12.6 Bq/L; and ^{222}Rn — 0.1–620 Bq/L. The substantial variation in gross alpha and beta activity across samples reflects geological diversity—particularly differences in water mineralization and chemical properties—as well as the inherent characteristics of the water types examined. In certain regions of Ukraine—specifically Vinnytsia, Cherkasy, Mykolaiv, and Kirovohrad—Σα activity likely exceeds the recommended level, reducing the benefits of screening water for Σα and Σβ activity in these areas.

Keywords: total alpha, ∑α, total beta, ∑β, ^{222}Rn, liquid scintillation counting, drinking water

Introduction

A substantial share of the world's drinking water supplies requires monitoring of hygienic parameters to determine whether they are suitable for consumption, particularly specific radionuclide activity concentrations [1, 2]. Some water is purified before consumption, while other water is purified after use. Both raw and purified water are regulated. Well water is considered less susceptible to contamination than surface water. Groundwater radioactivity depends on the

radionuclide content and mechanical properties of crystalline rocks, the water's chemical composition, and the duration of contact between water and rocks [3, 4].

The total activity of alpha and beta particles (∑α, ∑β) in drinking water serves as a screening measure of the total radioactivity emitted by alpha- and beta-emitting isotopes in a water sample. These indicators commonly help determine whether more detailed radionuclide analysis is needed. They are widely regarded as the first step in the radiological assessment of drinking water, and values below guideline levels indicate that further investigation is not necessary under many standards [5, 6, 7]. The ∑α limit — 0.1 Bq/L — is used in many regulatory documents; some others use 0.5 Bq/L as the upper limit, and water below this level is generally considered acceptable without further radionuclide testing [5, 6, 8, 9, 10]. The ∑β limit — 1.0 Bq/L — is also used, and water below this level is generally considered acceptable without further radionuclide testing [5, 8, 10].

The authors of [11] analyzed a statistical sample of research results on chemical factors in water and its radioactivity, showing that ∑α and ∑β activities exhibit pronounced spatial correlation and are correlated with certain water chemical indicators. They developed corresponding models to estimate and predict water quality [11].

The 12-year screening (2012–2024) in 16 districts of Beijing, China, covered surface waters (n = 474) and tap water (n = 410) [12]. It showed that the total alpha activity did not exceed 0.55 Bq/L in surface water and 0.5 Bq/L in tap water; the total beta activity was 0.8 Bq/L and 0.68 Bq/L, respectively. Overall, tap water had higher total alpha levels, while surface waters had higher total beta levels.

In southern Vietnam, researchers measured the ∑α- and ∑β-activities of 226 groundwater samples [13]. Activity levels are moderate: ∑α—(0.024 to 0.748 Bq/L), with an average of 0.183 ± 0.034 Bq/L, and ∑β—(0.027 to 0.632 Bq/L), with an average of 0.152 ± 0.015 Bq/L. Averages are significantly higher in untreated water.

Many studies found that measured ∑α- and ∑β-activities in drinking water were below recommended levels, confirming that these options are suitable and more affordable [14, 15, 16, 17, 18, 19, 20, 21].

Water radioactivity in Ukraine varies. Studies of Ukraine's water resources indicate that ∑α-activity and ∑β-activity levels are generally acceptable across many drinking water sources, but exceedances are observed in certain regions, particularly in groundwater, bottled water, and some reservoirs or water supply systems, especially where mineralization is elevated or natural radionuclides are present [22, 23, 24, 25, 26, 27, 28, 29, 30]. According to estimates in [28], which compared the gross alpha activity of drinking water from two aquifers used primarily in a selected

district of Kyiv city, water from the Bajocian aquifer contained 3.5 times the alpha emitters of water from the Cenomanian aquifer.

Legislation – legal issues

In Ukraine, regulations on total alpha and beta activity in potable water were established in 2010 [31]. This regulation [31] is two-tiered: at the first level, it adopts the WHO's main provision [2], which states that water is unconditionally safe with respect to radioactivity if its total alpha activity does not exceed 0.1 Bq/L and its total beta activity does not exceed 1.0 Bq/L. This statement is believed to apply to most water sources. Therefore, researchers use ∑α- and ∑β-activity to monitor compliance with the first-level requirements [31]. If these conditions are not met for groundwater sources [31], researchers consider an additional condition, borrowed from the national radiation standard [32]: non-exceedance of activity levels for the corresponding main dose-forming radionuclides. This condition for groundwater is — (^{222}Rn < 100.0 Bq/L, ^{226}Ra < 1.0 Bq/L; ^{228}Ra < 1.0 Bq/L; ∑U < 1.0 Bq/L). For surface water, the considered condition also includes (^{137}Cs < 2.0 Bq/L and ^{90}Sr < 2.0 Bq/L). To monitor compliance, we measure the concentrations of the individual radionuclides listed above, allowing us to assess the corresponding dose load for consumers of this water [25, 27, 33]. Ukrainian product enterprises presented on the European market face additional obligations under Euratom regulations [33]. We assessed more than 150 water samples, most of which were purified water [27], and found no exceedance of the 0.1 mSv/year dose limit [33].

Methods

Measurements of ∑α- and ∑β-activity typically use gas-flow detectors, solid scintillation detectors, and liquid scintillation counters. Proportional counters (gas-flow detectors) are a classic approach for screening ∑α- and ∑β-activity in drinking water [7, 14, 35, 36, 39, 40, 41]; solid scintillation detectors have also proven effective [35, 36, 39]. Liquid scintillation counters (LSC/LSS) are widely used and often considered faster, with simpler sample preparation and high detection efficiency [30, 37, 38, 39, 42, 43, 44, 45, 46]. LSC methods are considered the most convenient and promising, particularly those with lower detection limits [39]. Important issues when using different methods include quenching, self-absorption, sample mass, radionuclide-dependent detector response, and cross α/β interference during simultaneous measurements [6, 7, 47, 48, 49, 50, 51, 52].

These methods have been used for many years and are practiced by individual laboratories; some are recognized as international standards [35, 36, 37, 38]. The method selected depends on the availability of the necessary equipment and on national policies governing its selection and use

[39]. Key considerations include acceptable sensitivity, metrological support, and calibration traceability for the measuring device. In Ukraine, researchers commonly use available equipment, including liquid scintillation spectrometers.

Total α and β serve as an economically efficient, quick screening tool, but they are less specific and accurate than analyzing individual radionuclides [49, 53, 54].

Our methodical approach

The Radiation Monitoring Laboratory of the State Institution Marzieiev Institute of Public Health of the National Academy of Medical Sciences of Ukraine uses Quantulus 1220™ liquid scintillation spectrometers that have been in operation since 1988 and 2008, respectively.

Each request for water radioactivity testing is based on a specific regulatory document [31, 32, 34]. Accordingly, we provide consultation or recommendations on what to test in each case, drawing on our experience with previous studies [22, 25, 26, 27, 30, 33].

To prepare water samples for measuring total alpha and beta activity, evaporate 50 mL of water to dryness in a glass beaker on an electric stove. Add 1–3 mL of 35% hydrogen peroxide to help the sample illuminate, destroy any organic impurities, and promote evaporation for mineralized water. Using a glass rod, dissolve the dry residue in 2 mL of 1 M HNO_3, thoroughly rinsing the beaker walls and bottom. Transfer the resulting solution to a 20 mL disposable plastic vial. Then, using a glass rod as described above, rinse the beaker with 2 mL of distilled water and add the rinse to the vial. Add 16 mL of scintillation cocktail (Optiphase High Safe 3 or Supersolve X) to the resulting 4 mL solution. When switching to a new cocktail bottle, prepare a background sample as well and check it again if needed. Recently [25], we reported estimated sample losses of 3.3±0.9% (N=5) when concentrating 100 mL of water; when concentrating 50 mL, the loss is 2.8±0.9% (N=5). For some highly mineralized water samples, we washed the dry residue sequentially with two 2 mL portions of 1 M HNO_3, followed by two 2 mL portions of distilled water (8 mL total), of which we used only 4 mL.

The sample measurement procedure preset for any sample in the laboratory includes several measurements (30 or 60 min each). We performed statistical analyses by region of interest and calculated cumulative spectra that allowed us to exclude individual outliers using the EasyView program.

Radon in water was measured as described earlier [22, 25, 26, 27, 30, 33]. We added 10 mL of a water-immiscible scintillation cocktail (4 g/L PPO and 0.1 g/L POPOP in o-xylene) to 10 mL of each water sample in a glass vial. After shaking each sample for 1 min, we counted it with an LS spectrometer for at least 10 min. Counting times ranged from 10 to 100 min. For calculations, we used the spectral interval corresponding to the sum peak of ^{222}Rn and ^{218}Po.

We use preset optimal PSA circuit parameters for each spectrometer and scintillation cocktail type, based on typical samples, because the circuits differ between devices purchased in 1988 and 2008. In addition to the traditional approach of calibrating α/β separation with ^{241}Am and ^{90}Sr sources, we use a depleted uranium sample in which ^{238}U is in equilibrium with ^{234}Th and ^{234}Pa. During simultaneous registration of α- and β-radiation spectra, the alpha-emitter peak lies between the ^{234}Th and ^{234}Pa peaks. 'Pure' spectra—with no crossover between α and β—correspond to the optimal PSA parameter (see Fig. 1). In some cases, individual samples had to be remeasured under different α/β separation conditions, using a more suitable PSA value, especially when ^{40}K or ^{90}Sr activity concentrations were elevated. Good laboratory practice involves conducting comparative tests [25, 54, 55, 56, 57, 58].

We visually analyze and compare sample spectra. The alpha spectrum peak, if present, sometimes appears at higher energies and corresponds to ^{224}Ra and its daughter products, which are the predominant components [59]. In such cases, we use wider spectra section to calculate ∑α activity.

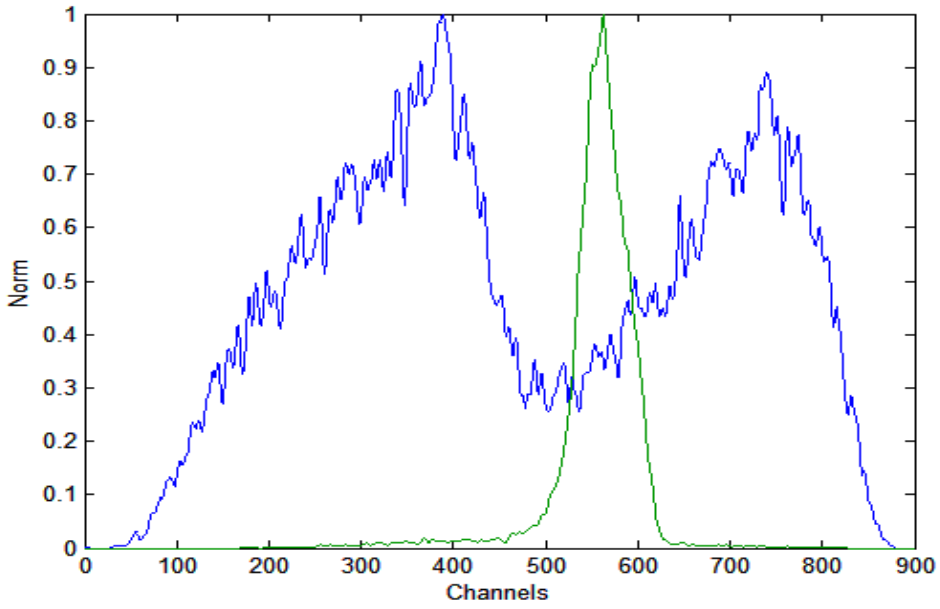


Fig. 1 – Normalized spectra of depleted uranium in optimal α-/β- separation condition

Activity calculation

We calculated the activity concentrations ∑α, ∑β, and ^{222}Rn using Formulas 1 and 2. We accounted for the sample count rate (CPM), background (BG), and counting efficiency (E) for the corresponding spectral windows as follows: for ∑α (Formula 1), the α–spectrum window was 450 to 650 channels; for ∑β (Formula 1), we used the sum of the β-spectrum window (150 to 950 channels) and the α-spectrum sub-windows (100 to 449 channels and 651 to 950 channels).

$$A_{\sum\alpha} = \frac{(CPM-BG)}{E \cdot V \cdot 60} \text{ (Bq/L);} \qquad (1)$$

$A_{\sum\alpha}$ – total α-activity concentration;

CPM – Sample count rate (counts per minute);

BG – Background sample count rate (counts per minute);

E - Counting efficiency, ~100% for α, and ~100% for β;

V – Corresponding water sample volume, L (0.050).

When calculating the ^{222}Rn activity of the samples (see Formula 2), we [25, 33] used the actual water sample volume (V = 10 mL) and accounted for ^{222}Rn decay over the interval from sampling to measurement.

$$A_{Rn} = \frac{(CPM-BG)\cdot e^{\frac{0{,}693\cdot\Delta T}{3{,}82}}}{E\cdot V\cdot 60}\ (\text{Bq/L});\qquad (2)$$

A_{Rn} – ^{222}Rn activity concentration;

CPM – Sample count rate (counts per minute);

BG – Background sample count rate (counts per minute);

ΔT – Sample delay time interval, from sampling to counting, days;

0.693 = log(2);

E - Counting efficiency, for the counting window corresponding to ^{222}Rn+^{218}Po (~200%);

V – Corresponding water sample volume, L.

Using the sample preparation scenarios above and a measurement time of 300 minutes, the minimum detectable activity (MDA) is 0.01 Bq/L for ∑α and 0.05 Bq/L for ∑β, according to Formula 3 [25, 60]. For 222Rn measurements, the MDA was 0.25 Bq/L for 20 min of counting and about 0.1 Bq/L for 100 min of counting.

$$MDA = \frac{2\cdot\sqrt{BG\cdot T}}{M\cdot T\cdot Error\cdot 60\cdot Eff}\qquad (3)$$

MDA - minimum detectable activity;

BG – background count rate, CPM ;

T – counting time, min;

M – sample volume, L;

Error – uncertainty, percent (30%);

60 – time units conversion factor, sec/min;

Eff – counting efficiency above.

Samples's set

The scope covers all samples the laboratory received for ∑α- and ∑β-activity analysis in water from 2021 through June 2026. The data report ∑α-, ∑β-, and ^{222}Rn activity concentrations in the corresponding samples. These include raw or treated well water; ready-to-drink water from wells or surface sources; discharge water (in some cases, water collected where it enters a river or lake); and water collected upstream and downstream of discharge points. We analyzed most samples at clients' request. As agreed, we publish the data only in generalized form, without detailed information about sampling locations or owners.

Measurement data and their discussion

The dataset is presented as is. It includes 469 results across six water types and twenty regions of Ukraine. We present summary data for ∑α, ∑β, and ^{222}Rn activity concentrations in water samples as distributions (Fig. 2) and statistical summaries (Tables 1 and 2) for each indicator. The distributions—box-and-whisker plots—are constructed using the decimal logarithms of each indicator. The data for each indicator are highly uneven. Untreated water shows high outliers in the ∑α distribution plot, whereas treated water shows more low outliers in the ∑β distribution plot. The samples correspond to the water types studied (Table 1) and the territorial regions (Table 2). Each table presents the data element-wise—starting with the most abundant. To perform the statistical estimates, we used an approach similar to that described in [61, 62, 63]. For samples with activity below the MDA, we treated them as half the MDA. Each indicator spans the corresponding interval: ∑α (0.005–7.3 Bq/L), ∑β (0.02–12.6 Bq/L), and ^{222}Rn (0.1–620 Bq/L).

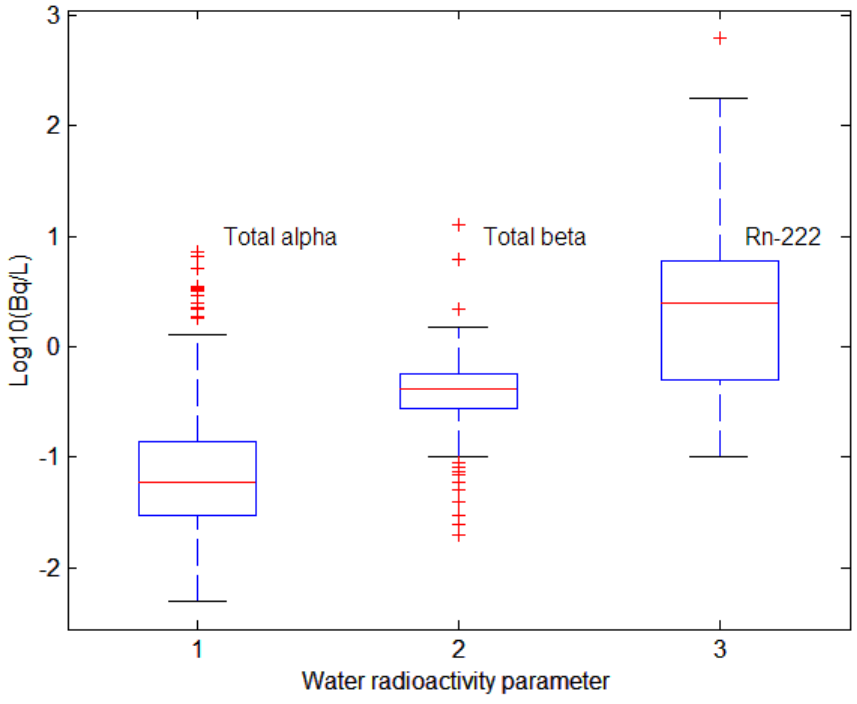


Figure 2 – Distribution of water radioactivity parameters among all samples (1 - ∑α; 2 - ∑β; 3 - ^{222}Rn)

Table 1 presents statistical data for water types, including raw and processed samples: underground (385), discharge (33), surface (22), tap (19), mine (6), and bottled (4). Groundwater is the most common type.

Table 1 – Statistical data on activity concentration (∑α, ∑β, ^{222}Rn) by water type (Bq/L)

Water type	N	Indicator	min	max	mean	std	median	iqr
All samples	469	∑α	0.005	7.3	0.25	0.69	0.06	0.11
		∑β	0.02	12.6	0.48	0.67	0.41	0.29
		^{222}Rn	0.1	620	8.9	33.3	2.5	5.5
Underground	385	∑α	0.005	7.30	0.26	0.69	0.06	0.14
		∑β	0.02	12.60	0.50	0.73	0.42	0.30
		^{222}Rn	0.1	620	10.3	35.9	3.5	7.0
Discharge	33	∑α	0.005	0.46	0.06	0.09	0.04	0.05
		∑β	0.06	0.76	0.36	0.19	0.32	0.24
		^{222}Rn	0.2	3.0	0.88	0.74	0.50	0.56
Surface	22	∑α	0.005	1.24	0.18	0.31	0.09	0.11
		∑β	0.13	0.92	0.46	0.19	0.43	0.25
		^{222}Rn	0.25	2.0	0.69	0.54	0.50	0.75
Tap	19	∑α	0.005	6.50	0.39	1.48	0.03	0.08
		∑β	0.09	1.10	0.37	0.22	0.37	0.24
		^{222}Rn	0.25	144	8.7	32.8	0.50	0.92
Mine	6	∑α	0.03	0.76	0.34	0.31	0.22	0.56
		∑β	0.26	0.77	0.49	0.19	0.51	0.32
		^{222}Rn	0.30	0.50	0.43	0.10	0.50	0.20
Bottled	4	∑α	0.01	0.09	0.06	0.04	0.07	0.06
		∑β	0.21	0.59	0.38	0.19	0.36	0.33
		^{222}Rn	0.50	6.60	2.03	3.05	0.50	3.05

Table 2 presents statistical data on radioactivity indicators in water samples by region, ranked from the highest to the lowest number of samples. Kyiv and its surrounding area account for the most samples, followed by Vinnytsia and Chernihiv, then Cherkasy, Mykolaiv, Poltava, and Odesa. The Zhytomyr region is underrepresented, likely because local laboratories measure ∑α and ∑β activity in water, whereas our laboratory has mainly studied corresponding samples by nuclide [25, 33]. In other cases, at request, we recommend detailed analyses of radionuclide activity concentrations, as the ∑α and ∑β limits are expected to be exceeded. The corresponding data are analyzed in [25, 27, 33].

As shown in Table 2, median total alpha activity in the Vinnytsia, Cherkasy, Mykolaiv, and Kirovohrad regions is close to or above the national regulatory limit of 0.1 Bq/L [31]. This pattern

is consistent with previous studies [29, 30]. When discussing testing options with clients from these regions, we consider this and recommend radionuclide-specific testing from the outset.

Conclusions

Numerous independent studies worldwide concur on the importance of screening, selecting appropriate activity-concentration thresholds, and using primary methods to measure ∑α- and ∑β-activities in water [5, 10, 42].

Total alpha/beta analysis is an economical, rapid, and useful screening tool, but it is less specific and accurate than analyzing individual radionuclides [50, 53, 54]. It is sufficient when most water samples comply with regulatory requirements.

We sent each client the individual results for each analyzed sample, along with a conclusion on whether the water's radioactivity parameters met the regulatory standard [31] or a recommendation for radionuclide-specific analysis to inform water treatment decisions.

The dataset covers radioactivity intervals of ∑α: 0.005-7.3 Bq/L, ∑β: 0.02-12.6 Bq/L, and ^{222}Rn: 0.1-620 Bq/L. Coverage is uneven across regions and water sample types, with the Kyiv region and groundwater best represented.

We used the data analyzed in this study only to assess compliance with the regulatory standard [31] and compare individual sample data. Unlike [25, 33], this paper does not analyze measurement results for each sample or assess the corresponding radiation doses.

Our recommendations are based on statistical data from studies of ∑α and ∑β activity by region, including whether radionuclide testing of water radioactivity is warranted. In some regions of Ukraine—Vinnytsia, Cherkasy, Mykolaiv, and Kirovohrad—the likelihood that ∑α activity will exceed the limit is high, which reduces the benefits of screening for ∑α and ∑β activity in water in these areas.

Acknowledgement

The authors thank Valentyna Yarmolenko, Nadiya Pozdnyakova, and Viktor Sakhno for their care in preparing the water samples for LS counting.

Funding declaration

No Funding

Data availability

All data generated or analyzed during this study are included in this published article [and its supplementary information files].

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