

A Rapid Extraction Procedure for the Determination of Strontium-90 in Water Samples

Markus Zehringer, Johannes Abraham, Franziska Kammerer, Vlora Syla and Michael Wagmann
State Laboratory Basel-City, Kannenfeldstrasse 2, Basel 4056, Switzerland

Abstract: A beta spectrometric method for the rapid determination of strontium-90 (^{90}Sr) in water samples was developed and tested. ^{90}Sr is extracted directly from the water samples by means of a scintillator cocktail, containing the crown ether dicyclohexano-18-crown-6 as an extracting agent (STRONEX[®]). Minimal clean-up is necessary when other beta nuclides are present, such as barium-140. These nuclides are eliminated by a barium chromate scavenge, prior to the extraction step. The method presented here allows for the investigation of at least 12 water samples a day and is therefore a suitable tool for emergency analysis.

Key words: Strontium-90, beta spectrometry, emergency analysis, STRONEX[®].

1. Introduction

Authors have estimated the release of radio nuclides from the core meltings at the Fukushima Dai-ichi NPP (nuclear power plant) at 153-160 PBq of ^{131}I , 26 PBq of radio caesium ($^{134+137}\text{Cs}$) and ~0.3 PBq of radio strontium (mainly ^{90}Sr) [1]. In 2012, Povinec reported ^{90}Sr levels in the seawater near to the Fukushima NPP. They measured ^{90}Sr activities of up to 400 Bq/L [1, 2]. Limited data are available for ^{90}Sr due to its complicated and time-consuming sample preparation [3]. ^{90}Sr is a pure beta emitter and therefore one has to prepare pure beta sources, meaning extraction and clean-up of the sample, before it can be analysed by beta spectrometry.

Fast radio analysis is an important instrument in emergency management concepts. In Switzerland, distinguished radiology laboratories have to be prepared for radiological impacts or accidents. For many important radionuclides, such as ^{133}Xe , ^{106}Ru , ^{131}I , ^{140}Ba , ^{140}La , ^{134}Cs and ^{137}Cs , the radiology labs are well equipped with gamma ray detection systems to analyse environmental and food samples within a short period.

Corresponding author: Dr. Markus Zehringer, research fields: radiochemistry, radioprotection.

Two main analytical strategies exist for the analysis of ^{90}Sr . One approach consists of analysing ^{90}Sr after enrichment by selective precipitation and separation from disturbing beta nuclides, such as ^{40}K . The other approach is to isolate the daughter nuclide of ^{90}Sr , ^{90}Y , which is in equilibrium with ^{90}Sr . $^{90}\text{Sr}/^{90}\text{Y}$ are enriched by precipitation. Then, one separates ^{90}Y from ^{90}Sr by precipitation and measures this beta source with beta spectrometry. The beta decay of ^{90}Y (half-life of 64 h) is measured through several consecutive runs by means of a beta gas proportional counting system. This method is highly sensitive and suitable for activities in the mBq range; but is time consuming. Therefore, this approach is not appropriate for emergency management analysis [4-6].

The so-called “fast methods” are based on the selective extraction of strontium, either by the means of crown ethers fixed on chromatography columns, such as Amberlite XAD or amberchrome resins, or by using ion exchange chromatography. Their use is well described in the literature, and extraction resins are available commercially [7]. The isolated strontium nuclides are analysed with a liquid scintillation counter. These methods are clearly understood and suitable for ^{89}Sr and ^{90}Sr . Other fast method approaches include batch extractions with Chelite and

other adsorbents [8-14]. Other authors use Cherenkov counting of ^{89}Sr and ^{90}Y . First, ^{89}Sr and ^{90}Sr are enriched and precipitated. After the elimination of ^{90}Y , ^{89}Sr is analysed by Cherenkov counting without a scintillator. The sum of ^{89}Sr and ^{90}Sr is then measured after adding a scintillator. After the in growth of ^{90}Y (20 d), a second Cherenkov counting gives the sum of the activities of ^{89}Sr and ^{90}Y [15, 16].

Another promising approach is the liquid/liquid extraction of radio strontium with crown ethers. In the 1980s, McDowell used several crown ethers, such as dibenzo-18-crown-6 or dicyclohexano-18-crown-6 (DC18C6), in combination with the scintillator didodecyl naphthalene sulfonic acid (HDDNS) combined with a water insoluble solvent (toluene). The partition coefficient P for strontium is about 6,000 and most alkaline and alkaline earth metals show poor affinity for DC18C6 [17-19].

The aim of the present study is to develop a robust, fast extraction procedure based on the work of McDowell for the determination of ^{90}Sr in water samples, such as river water and seawater.

2. Experiment

2.1 Sampling

The first extractions were executed with deionised water (> 16 Mohm electrical resistance). The most important matrix at an emergency case is drinking water. The authors chose tap water from the city of Basel, available at our laboratory. Second, we investigated river water from several rivers in our county. The authors took water from the river Rhine (upstream from the city of Basel, Rhine-km 158 at Muttenz, Schweizerhalle), from the river Wiese (at Lange Erlen, Basel) and from the river Birs (at St. Jakob, Basel-City). The authors collected all samples in 20 L containers and transported them without any preservation to the lab. All samples were random samples. Seawater was obtained from a seafish and coral shop. This natural seawater was from the Atlantic Ocean (North Sea) and was provided by ATI

Aquaristik, Germany [20].

2.2 Materials and Methods

STRONEX[®] is an extractive scintillator available from Ordela Inc. at Oak Ridge, TN, USA [21]. This cocktail is specially designed for the selective extraction of strontium. It contains DC18C6 as an extracting agent and HDDNS as a scintillator diluted in toluene. All reagents, such as NaNO₃, KNO₃, BaCl₂, Bi(NO₃)₃ and NaOH, were of analytical grade and obtained from Merck, Darmstadt. Scintillation vials were from Perkin Elmer Life Sciences. Folded paper filters were from Schleicher and Schuell (Whatman 604 1/2, 2 µm, 150 mm diameter). The authors used a ^{90}Sr reference solution from LMRI¹. For the recovery experiments, different dilutions of the reference standard were prepared in 10% HCl. A reference solution of ^{133}Ba from medipro² was used for the first barium chromate scavenge experiments. Commercially available STRONEX[®] contains a lipophilic acid, which is only stable in the acid form. It has to be converted into the ionic form. Before use, 8 mL of a mixture of NaNO₃ and NaOH (4 mL of 0.6 M NaNO₃ and 4 mL of 0.4 M NaOH) had to be mixed with 8 mL of STRONEX[®] in a 20 mL plastic centrifugal vial. The conditioned STRONEX[®] was added to 1 L of water sample for extraction [21].

2.3 Sample Preparation

All samples were extracted in 1 L glass bottles. Undissolved particles were removed by filtration over a paper filter. The pH value was adjusted between 10 and 10.5 by adding NaOH. The STRONEX[®] was preconditioned as described in Section 2.2 and then added to 1 L of filtered sample, which was then stirred vigorously for 5 min. The phases were allowed to separate for a maximum of 1 h. The upper scintillator

¹Laboratoire de métrologie des rayonnements ionisants (LMRI): 413.3 kBq/g ^{90}Sr -activity. Reference date: 13.12.1983. Standard solution with carrier of 10 µg/g $^{90}\text{Y}(\text{NO}_3)_3$ and $^{90}\text{Sr}(\text{NO}_3)_2$ each, solved in 0.1 N HNO₃.

²Certified by LMRI: 4.57 MBq ^{133}Ba in HCl, reference date: 10.8.1984.

phase was removed using a micro separator system from AMSI-Glas AG as follows (Fig. 1). Distilled water is added through entrance A to move the STRONEX® phase up into the separator chamber. The lighter STRONEX® phase moves over outlet B to be collected in a 20 mL scintillation vial. In some cases, surface active substances caused the build-up of emulsions. Therefore, the separation was not satisfactory and the STRONEX® phase contained some water droplets. The authors removed this water by centrifugation at 4000 rpm for 5 min. At least 4 mL of the STRONEX® phase was transferred into a 20 mL scintillation vial. No further addition to the scintillation vial was necessary as STRONEX® already contains the scintillator.

For each recovery experiment, two samples were extracted. The first sample was a native sample without the addition of ^{90}Sr , followed by the same water sample with a defined addition of ^{90}Sr activity, A_{add} . The recovery, R, is calculated according to Eq. (1) as follows:

$$R = (A_x - A_o)/A_{\text{add}} \quad (1)$$

A_x : measured activity in spiked sample extract, A_o : measured activity in native sample extract, A_{add} : added ^{90}Sr -activity to sample x.

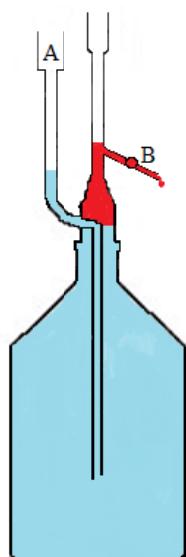


Fig. 1 Microseparator for the liquid/liquid extraction of water (grey) with a small extraction volume of STRONEX® (black).

A_x , A_o : measured STRONEX® extract has to be corrected to the initially added volume of 8 mL, as only a part of the added 8 mL of the cocktail can be recovered (4-5 mL).

With a partition coefficient, P of 6,000 for the crown ether contained in STRONEX® [19], the theoretically achievable extraction recovery of a unique extraction is calculated according to Eq. (2) as follows:

$$R (\%) = ((PV_{\text{org}})/(PV_{\text{org}} + V_{\text{aq}}))100 \quad (2)$$

With V_{aq} of 1 L and V_{org} of 8 mL, STRONEX® a theoretical extraction efficiency of 98% for ^{90}Sr should be achieved [22].

2.4 Beta Spectrometry

Liquid scintillation was performed with a scintillation system HIDEX 300SL counter from Hidex Oy. The samples were counted for 60 min in beta count mode. The ROI (region of interest) for ^{90}Sr was set to 50-350 keV (400-760 channels). One has to start the scintillation counting within a maximum of 5 h after the extraction step to avoid the ingrowth of ^{90}Y ($b_{\text{max}}\text{energy}$ of 2,288 keV). After 5 h, the ingrowth of ^{90}Y reached about 5% of the extracted ^{90}Sr activity. For quantitative analyses, the beta background counts of an equal volume of pure scintillator were subtracted.

3. Results and Discussion

The first ^{90}Sr extractions were performed with distilled water. The activity level was set to 1 Bq/L. Similar recoveries were obtained when the samples were extracted with 5 or 10 mL of STRONEX® (105% \pm 11% and 104% \pm 11%, respectively). The linearity of an activity row from 0.1 to 1 Bq/L was acceptable (0.998).

3.1 Optimisation of the Extraction Procedure

The authors first optimised several parameters from the proposed separation and analysis scheme of McDowell [19]. First, the amount of STRONEX®

extracting agent was optimised. The authors extracted ^{90}Sr from 1 L of river water using 3-10 mL of STRONEX[®]. With 5 mL of STRONEX[®], the recovery was only 76%. A recovery of 90% was achieved with a STRONEX[®] volume of 7 mL. The authors finally set the STRONEX[®] volume to 8 mL for the extractions of a 1 L sample volume.

To study the influence of pH at the extraction step, the authors chose water samples rich in calcium and bicarbonate (river Birs). The pH was systematically set to 5, 8, 9, 10 and 11. At pH 5, no strontium was extracted at all. At pH 10, a recovery of 65% was achieved. At a pH value 11, the authors noticed a precipitation of the hydroxides of Ca and Mg. Under these conditions, less than 20% of the added ^{90}Sr was extractable.

Finally, the influence of sodium chloride on the extraction behaviour of ^{90}Sr was tested. NaCl was added to tap water in different amounts of 30, 60, 120 and 300 g to reach a final salt content of 30%. No significant reduction in the recovery of ^{90}Sr (mean recovery $79 \pm 5\%$ at a level of 1 Bq/L ^{90}Sr) was noticed.

3.2 Influence of other Ions on the Extraction of ^{90}Sr with STRONEX[®]

There are two possibilities for how other nuclides may disturb the analysis of ^{90}Sr with STRONEX[®]. First, the capacity of the STRONEX[®] may be exhausted when high amounts of other ions are present in the water sample. Consequently, strontium recovery would be poor. Second, co-extracted beta nuclides may interfere in the beta liquid scintillation analysis, meaning that the results could potentially include overlapping beta spectra and erroneously added counts to the measured ^{90}Sr activity.

McDowell investigated the selectivity of crown ethers for alkali and earth alkaline metals [17]. When the cavity size of the crown ether corresponds with the diameter of the ion of interest, good extraction behaviour is expected. The cavity size of DC18C6 is

0.27 to 0.32 nm. There are two ions, Ba²⁺ and Sr²⁺, which can interact with DC18C6. They have ionic diameters of 0.27 and 0.23 nm and have distribution coefficients of 3,000 and 6,000, respectively [19].

The influence of barium on the extraction of strontium was tested using barium concentrations from 0-600 mg/L. From 0-5 mg/L of barium, the recovery of strontium remains relatively constant (about 70%). At 10 mg/L of barium and more, the recovery of ^{90}Sr drops. About 10% of ^{90}Sr is extracted when the water sample contains 600 mg/L of barium.

A value of 5 mg of ^{140}Ba corresponds to an activity of 2.10^{13} Bq due to its short half-life of 12.8 d. In an emergency scenario from the Institut de Radio physique (IRA), a ^{140}Ba activity of around 350 kBq/L was calculated (corresponding to 10^{-10} g/L) [23]. Therefore, the estimated concentration of ^{140}Ba at an emergency case (e.g. a NPP accident) is far below the disturbing concentration for the strontium extraction with STRONEX[®]. The typical level of barium in rivers lies between 20 to 50 µg/L and in seawater is about 10 µg/L [24], far below 10 mg/L. Therefore, barium should not interfere at the STRONEX[®] extraction step.

3.3 Influence of Co-extracted Beta Nuclides on Beta Spectrometry

In 2013, the IRA organised an interlaboratory test [23]. The aim of the test was to analyse short-lived radionuclides with high-resolution gamma ray spectrometry in the fallout of an accident at a NPP. In the event of such a disaster, there is expected to be a significant variety of beta radionuclides from elements, such as iodine, antimony, ruthenium, caesium, cerium, lanthanum and barium. Most of these nuclides decay with short half-lives of minutes to days. They calculated the possible emission of materials 2 and 11 days after release to the environment and proposed simulated gamma ray spectra. Several Ba nuclides were emitted. ^{140}Ba , a product from nuclear fission with a half-life of 306 h, is a betaemitter (b_{\max} of

1,020 keV). Its decay product is ^{140}La , also a beta emitter (b_{\max} of 2,200 keV and half-life of 40.3 h). While STRONEX® does not extract ^{140}La , ^{140}Ba is co-extracted and will erroneously add to the calculated strontium activity.

Two other barium nuclides are produced by the decay of other fission products, ^{136m}Ba (daughter of ^{136}Cs) and ^{137m}Ba (daughter of ^{137}Cs). Neither nuclide is a beta emitter and therefore do not interfere in beta spectrometry.

Normally, the first analysis of radioactive fallout is performed with gamma ray spectrometry, before starting time-consuming beta or alpha analyses. If ^{140}Ba is present, the typical gamma lines of ^{140}Ba , 162.7 (6.2%), 304.8 (4.3%), 423.7 (3.2%), 437.6 (1.9%) and 537.3 keV (24.4%) will be detected. ^{140}Ba has to be removed from water samples prior to beta analysis of ^{90}Sr .

One possibility to avoid the interference of ^{140}Ba would be to await the decay of this radionuclide (51 d). At this point, the ^{140}Ba activity will be below 6% of the original activity. This possibility is not an option for emergency analyses.

3.4 Barium Scavenge

The second possibility is to remove the ^{140}Ba from the sample prior to the extraction with STRONEX®. This can be done by a barium chromate scavenge [25]. Several water matrices were tested. The 90 mg of non-active barium chloride and 146 mg of potassium chromate were added to a 1 L of water sample spiked with ^{90}Sr . The pH of the water sample was set between 10 and 10.5. After 10 min, the barium

chromate precipitation was filtered off. The extraction with 8 mL of STRONEX® gave the following recoveries, listed in Table 1.

The Ba scavenge led to a certain loss of ^{90}Sr of 22-50%. In undiluted seawater, more than 70% of the added ^{90}Sr was lost. The scavenge was repeated with a 1:10 dilution of the seawater with distilled water, resulting in a loss of 36%. In the case, when ^{140}Ba is present and a barium scavenge is unavoidable, a recovery control with spiked samples is recommended.

3.5 Recovery Studies of Real Water Samples

All samples were extracted with 8 mL of preconditioned STRONEX® at a pH of 10.

First, the authors made spiking experiments with deionised water. Eight spiked samples with 1 Bq/L of ^{90}Sr showed a mean recovery of $105 \pm 11\%$.

3.5.1 Tap Water

Tap water of the town of Basel was analysed as a first matrix. After two minutes of rinsing, the tap water was collected in our laboratory. ^{90}Sr was added to tap water samples of 1 L in increasing activities of 1-1.000 Bq. A tap water sample without any addition of ^{90}Sr was analysed as a blank. Here, the recovery was $108 \pm 7\%$ over the whole range.

3.5.2 River Water

We tested the recovery of ^{90}Sr in water samples of different rivers. Water from the river Rhine was spiked with ^{90}Sr concentrations from 0.05-1.00 Bq/L. A good linear correlation was achieved. Recoveries ranged from 68-96% with a mean recovery of $82 \pm 11\%$ (Fig. 2).

Table 1 Barium scavenge of different water matrices to eliminate interfering beta-nuclides, notably ^{140}Ba .

Matrix	^{90}Sr added Bq/L	^{90}Sr found Bq/L	^{90}Sr loss %
Tap water	85.5	66.7	22
River water Rhine	85.5	61.2	40
River water Birs	85.5	43.6	49
Sea water	87.6	22.8	74
Sea water, diluted 1:10	856	548	36

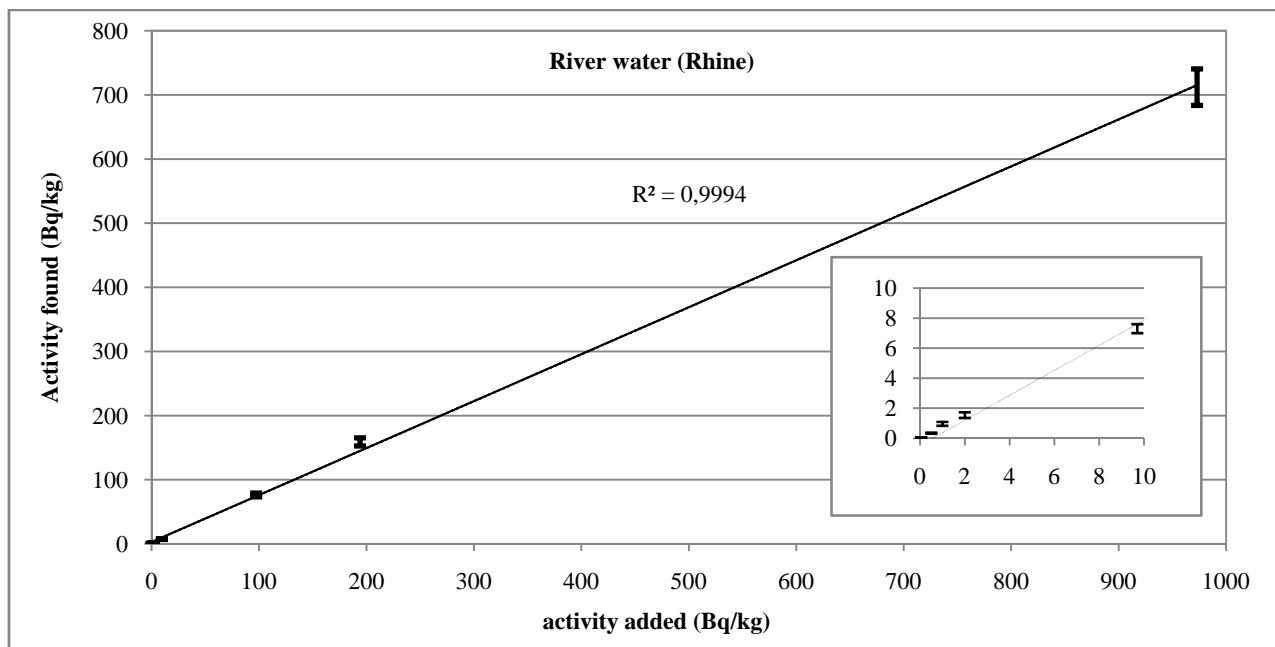


Fig. 2 Recoveries of ^{90}Sr in water of the river Rhine (error bars are the relative standard deviation of the liquid scintillation counting).

Table 2 Recovery experiments of ^{90}Sr in different, spiked water matrices (s.d.: relative standard deviation, n: number of analyses), DOC: dissolved organic carbon, n.d.: not detectable. ^a: data from [27], ^b: data, except Sr^{2+} , from [28], ^c: data of the seawater are from [20] except DOC [29], ^d: data from [30], ^e: data from [31].

Sample type	n	^{90}Sr added Bq/L	^{90}Sr found Bq/L	Recovery %	DOC mgC/L	Ca^{2+} mg/L	Mg^{2+} mg/L	Sr^{2+} mg/L	HCO_3^- mg/L
Deionised water	8	1.0	1.0 ± 0.11	105 ± 11	n.d.	n.d.	n.d.	n.d.	n.d.
River Rhine ^a	8	0.1-973	0.34 - 712	82 ± 11	1.9	48	7.5	0.5 ^b	163
River Wiese ^a	5	9.1	8.5 ± 2.7	93 ± 3	1.6	16	2.3	0.5 ^b	62
River Birs ^a	11	0.5-1.000	0.4 - 635	70 ± 11	3.1	82	4.7	0.5 ^b	272
Sea water ^c	5	5-1.000	5 - 905	92 ± 5	0.1-2.0	395	1.223	7.8	152
Reference sample ^d	10	19.22	18.3 ± 0.81	95 ± 5	-	-	-	4.0	-
Tap water from Basel ^e	5	1-1.000	1 - 1.045	108 ± 7	0.6	59	7.5	-	330

The recoveries found in other river water samples are summarised in Table 2. While recoveries in water from the river Wiese reached 93%, we observed significantly lower recoveries in water samples with higher ionic load, such as from the river Birs. This river water is rich in earth alkaline metals, e.g., 80 mg/L Ca, and HCO_3^- [26]. As mentioned above, there is a certain loss of ^{90}Sr at pH values >10 by coprecipitation with alkaline earth hydroxides or carbonates. As the precipitation at pH 10 is a slow process, we could avoid greater losses of ^{90}Sr by the immediate extraction with STRONEX® after setting the pH to 10. By taking care not to lose time after setting the pH, the authors were able to extract $70 \pm 11\%$

of the spiked ^{90}Sr .

3.5.3 Seawater

The extraction of 1 L of filtrated seawater gave poor recoveries of ^{90}Sr (about 30%). When setting the pH to 10, a bluish-white precipitate occurred, which led to the coprecipitation of the spiked ^{90}Sr . In seawater, the total dissolved substances are 288 times higher than in river water. According to Murray, the following ions are most dominant in seawater: Mg (150-300 times higher than in river water), Na (1.670), K (170), Cl (2.400), SO_4 (245) and Ca (27). Therefore, a major influence on the extraction behaviour of ^{90}Sr may be expected from Mg^{2+} . In addition, DOC (dissolved organic carbon) can be excluded as a

disturbing factor. River and seawater show similar DOC levels [27].

To avoid precipitations, we diluted 100 mL of seawater with 900 mL of distilled water before the extraction with STRONEX®. In diluted seawater no precipitation occurred at pH 10. The extraction of ⁹⁰Sr with 8 mL of STRONEX® was almost complete over a range from 5-1,000 Bq/L. An overall mean recovery of $92 \pm 5\%$ was achieved (Table 2).

Reference Material

A superficial water sample (synthetic water) from an interlaboratory test was analysed. The sample contained ⁹⁰Sr, ⁶⁰Co, ¹³⁷Cs, ¹³⁹Ce and ¹⁵²Eu with known activities between 12 and 32 Bq/L, and was stabilised with 65% HNO₃ (pH 1.9) [29]. The sample also contained the non-activetracers Sr²⁺, Co²⁺ and Ce³⁺ for stabilisation purposes (5 mg/L each). The asserted activity of ⁹⁰Sr was 19.2 Bq/L. A 100 mL sample was extracted with 8 mL of STRONEX®. The mean recovery of ten extractions was satisfactory with 18.2 ± 4.0 Bq/L, resulting in a mean recovery of 95% (Table 2).

4. Conclusions

In this work, it presented a simple extraction procedure for ⁹⁰Sr with the commercially available extracting agent STRONEX®. The procedure is a robust and fast method, which allows results within half a day, even for samples containing beta active fission nuclides. Therefore, this procedure is suitable for emergency analyses of water samples where time is the limiting factor.

First, the sample is analysed with gamma ray spectrometry. This gives an overview of the present fission nuclides and its decay products in the water sample. When ¹⁴⁰Ba is present, it has to be removed with a barium chromate scavenge before the beta analysis. This results in a certain loss of the analyte. Therefore, the recovery in samples with higher ionic load (e.g., seawater) has to be controlled by analysing spiked samples. Within 24 h, it should be possible to

analyse and report the results of at least 12 water samples using one liquid scintillation counter.

The detection limits were calculated according to DIN for several water matrices.

Extraction of 1 L of river water with 8 mL of STRONEX® and the final beta spectrometry of the 4 mL recovered STRONEX®-phase resulted in a detection limit of 0.1 Bq/L. Seawater, which is analysed in a 1:10 dilution with distilled water, has a detection limit of 1 Bq/L.

The costly STRONEX® reagent can be reused several times. The authors developed a clean-up procedure for STRONEX®. The authors extracted 100 mL of used STRONEX® thrice with 10 mL of 1 M hydrochloric acid each, using a separation funnel. The cleaned STRONEX® was washed with distilled water to achieve a pH of 3 (STRONEX® is only stable in an acidic medium). The cleaned STRONEX® was then purged with argon gas and kept at 5 °C in the dark. After a third washing step, more than 97% of the strontium was removed from the STRONEX®.

References

- [1] Povinec, P., and Hirose, K. 2012. "Aoyama, M. Radiostrontium in the Western North Pacific: Characteristics, Behaviour, and the Fukushima Impact." *Environ. Sci. Technol.* 46: 10356-63.
- [2] Hirose, K. 2011. "Fukushima Dai-ichi Nuclear Plant Accident: Summary of Regional Radioactive Deposition Monitoring Results." *J. Environ. Radioactivity* 111: 13-7.
- [3] Nies, H. 2015. "Fukushima Daiichi. Eintrag Radioaktiver Stoffe ins Meer." *Nachrichten aus der Chemie* 63: 525-31.
- [4] Erard, M., and Zimmerli, B. 1988. "Bestimmung von Strontium-90 in Milch." *Mitt. Gebiete Lebensm. Hyg.* 79: 48-56.
- [5] Geering, J., Friedli, C., and Lerch, P. 1990. "Method of Determination of Strontium-90 in the Environment." *J. Trace & Microprobe Techn.* 8: 211-30.
- [6] IAEA (International Atomic Energy Association). 1989. *Measurement of Radionuclides in Food and the Environment*. A Guidebook. Technical Reports Series 295: 70-91.
- [7] http://www.eichrom.com/products/info/sr_resin.aspx (Accessed May 19, 2017).
- [8] Dietz, M., Horwitz, E., Nelson, D., and Wahlgren, M.

1991. "An Improved Method for Determining ^{89}Sr and ^{90}Sr in Urine." *Health Physics* 61: 871-7.
- [9] Clark, S. 2005. "Separation and Determination of Radiostrontium in Calcium Carbonate Matrices of Biological Origin." *J. Radioanal. Nucl. Chem.* 194: 297-302.
- [10] Günther, K., Lange, S., and Veit, M. A. 2009. "Rapid Method for Determining ^{89}Sr and ^{90}Sr by Cerenkov Counting." *Appl. Radiation and Isotopes* 67: 781-5.
- [11] Kameo, Y., Katayama, A., Fujiwara, A., Haraga, T., and Nakashima, M. 2007. "Rapid Determination of ^{89}Sr and ^{90}Sr in Radioactive Waste using Sr Extraction Disk and Beta Ray Spectrometry." *Radioanal. Nucl. Chem.* 274: 71-8.
- [12] Szabo, G., Guczi, J., and Stur, D. 1987. "Preparation of 8-Hydroxyquinoline Substituted Silica Gel for Determination of Strontium-90 from Natural Water." *J. Radioanal. Nucl. Chem.* 111: 441-8.
- [13] Zou, Y., Liang, J., and Chu, T. 2017. "Crown Ether-Ionic Liquid-Based Extraction Chromatographic Resin for Separation of ^{90}Y from ^{90}Sr ." *J. Radioanal. Nucl. Chem.* 311: 1643-8.
- [14] Pimpl, M. 1995. " $^{89}\text{Sr}/^{90}\text{Sr}$ -Determination in Soils and Sediments using Crown Ethers for Ca/Sr-Separation." *J. Radioanal. Nucl. Chem.* 194: 311-8.
- [15] Todorokvic N. 2017. " ^{90}Sr Determination in Water Samples Using Cerenkov Radiation." *J. Environ. Radioactivity* 169/170: 197-202.
- [16] Tayeb, M., Dai, X., and Sdraulig, S. 2016. "Rapid and Simultaneous Determination of Strontium-89 and Strontium-90 in Seawater." *J. Environ. Radioactivity* 153: 214-21.
- [17] McDowell, W., Case, G. N., and Aldrup, D. 1983. "Investigations of Ion-Size-Selective Synergism in Solvent Extraction." *Sep. Sci. Technol.* 18: 1483-507.
- [18] McDowell, W. 1988. "Crown Ethers as Solvent Extraction Reagents: Where do we Stand?" *Sep. Sci. Technol.* 22: 1251-68.
- [19] McDowell, W. 1995. "Proposed Separation and Analysis Scheme for Strontium." ETRAC Inc. Accessed October 11, 2017. <http://www.ordela.com>. Accessed October 11, 2017.
- [20] http://atiaquaristik.com/de/?page_id=256/#Analysen. (Accessed May 19, 2017).
- [21] Oak Ridge Detector Laboratory, Ordela Inc. home Page. Accessed October 11, 2017. <http://www.ordela.com>(Accessed May 19, 2017).
- [22] McDowell, W. J., and McDowell, B. L. 1994. "Liquid Scintillation Alpha Spectrometry." Boca Raton-Ann Arbor-London-Tokyo: CRC Press.
- [23] Buchillier, T., Baillat, C., Laedermann, J., and Leupin, A. 2015. "Rapport Sur l'exercice d'analyse de Spectre de Centrale nucléaire 2013." Rapport Interne de l'Institut de Radiophysique, Lausanne, Switzerland.
- [24] Puchelt, H. 1967. "Zur Geochemie des Bariums im exogenen Zyklus." Springer: Heidelberg. ISBN: 978-3-642-46100-2.
- [25] Harvey, B., Ibbett, R., Lovett, M., and Williams, K. 1989. "Analytical Procedures for the Determination of Strontium Radionuclides in Environmental Materials." In *Aquatic Environment Protection: Analytical Methods Number 5*, edited by the Ministry of Agriculture, Fisheries and Food Directorate of Fisheries Research, Crown: Lovestoft, 4-33. ISSN: 0953-4466.
- [26] Zehring, M. 1995. "River Water Monitoring in Basel-City 1994." Report of the Water Protection Agency Basel-City. DOI:10.13140/RG.2.2.16667.26408.
- [27] Murray, J., and Ingalls, A. 2006. Oceanography 400 - Autumn 2006. Chemical Oceanography. Lecture Notes, Chp. 4: Major Ions in Sea Water. Accessed October 11, 2017. https://www.ocean.washington.edu/courses/oc400/Lecture_Notes/CHPT4.pdf&spf=1496663997469
- [28] Schmassmann, H. 1988. "Hydrochemische Synthese Nordwestschweiz: Tertiär- und Malm-Aquifere." Edited by Nagra, Technischer Bericht 88-07: 91.
- [29] Accessed October 11, 2017. [http://www.nagra.ch/data/documents/database/dokumente/\\$default/Default%20Folder/Publikationen/NTBs%201987-1988/d_ntb88-07.pdf](http://www.nagra.ch/data/documents/database/dokumente/$default/Default%20Folder/Publikationen/NTBs%201987-1988/d_ntb88-07.pdf) (Accessed May 19, 2017).
- [30] Thurman, E. M. 1985. "Organic Geochemistry of Natural Waters." M. Nijhoff and Dr. W. Junk Publ.: Dordrecht - Boston-Lancaster, 25. ISBN:978-94-010-8757-0.DOI:10.1007/978-94-009-5095-5.
- [31] Bünger, T. 2013. "Bestimmung von Strontium-89 und Strontium-90 in Wasser mit Schnellmethoden 2013, Ringversuch 5/2013." edited by Bundesamt für Strahlenschutz Berlin, Germany.
- [32] Wülser, R., and Schnyder, D. 1995. "Untersuchungsbericht Zur Qualitätssicherung am Basler Trinkwasser. Untersuchungsjahr 1994 und Untersuchungsperiode 1990-1994." Industrielle Werke Basel.