

Characterization of environment relevant nanoparticles with large facilities

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1. Introduction

Maintaining and restoring the quality of water, air and soil, so that the earth will be able to sustainably support human and other life, is one of the great challenges of our time. The scarcity of water, both in terms of quantity as well as quality, poses a significant threat to the well-being of people, especially in developing countries. Environmental nanotechnology is considered to play a key role in the shaping of current environmental engineering and science. Looking at materials at the nanoscale has stimulated the development and use of novel and cost effective technologies for remediation, pollution detection, catalysis and others. There is the huge hope that nanotechnological applications and products will lead to a cleaner and healthier environment. Great hope is also placed on the role that nanotechnology can play in providing efficient and cheap access to clean water for developing countries.

Particles in the nanosized range have been present on earth for millions of years and have been used by mankind for thousands of years. Nanoparticles occur naturally in the environment in the atmosphere in the form of aerosols, in aquatic systems as colloids, and in soils and the subsurface in a variety of biogenic and geogenic materials. Nanoparticles are also formed as an unintended by-product from human activities during combustion of fossil fuels or biomass. All these types of nanoparticles are also deliberately produced as engineered nanoparticles, in addition to a wide array of newly synthesised forms. These particles are either released unintentionally into the environment or are introduced on purpose, e.g. during remediation of polluted soils.

Environmental systems such as soils or sediments are often complex composite materials involving organic and mineral structures, which constituting important barriers towards pollutions. In order to exploit and enhance these natural strategies with nanoparticles and nanotechnology in environmental nanotechnology, more structural information is needed, which can ideally be provided by synchrotron radiation and neutron facilities, if the appropriate analytical environment is delivered.

Clean water is a requirement for all properly functioning societies worldwide, but is often limited. New approaches are continually being examined to supplement traditional water treatment methods. These need to be lower in costs and more effective than current techniques for removal of contaminants from water. In this context, nano-technological approaches are also considered. Nanoparticles are used as potent adsorbents, in some cases combined with magnetic particles to ease particle separation; nanoparticles used as catalysts for chemical or photochemical destruction of contaminants; nanosized zero-valent iron used for removal of metals and organic compounds from water; and nanofiltration membranes. The most effective methods are likely to consist of more than one of these technologies in a hybrid system.

In this article we will focus in systems with environmental relevance, like clays and their interaction with aqueous solutions, which are of great importance for radioactive waste

management. In a repository of high-level radioactive waste the buffer material should perform certain barrier functions in order to isolate and support the waste canisters. It is expected to minimize the flow rate of percolating groundwater, to withstand mechanical stress in the host rocks, and to seal open cracks and fissures. The main function of the clay material is to retard the migration of the radionuclides in case of corrosion of the waste package material. Bentonite, a natural clay widely used in industry, was selected as the most suitable buffer material for the high-level radioactive waste repository (Güven 1990). Montmorillonite, the main component of bentonite, is a swelling clay consisting in negatively charged aluminosilicate layers held together by interlayer cations. Under humid conditions the interlayer cations and the internal clay surfaces are hydrated. The exchange of interlayer cations is the main mechanism of radionuclide retention by smectites. The study of the hydration and hydrolysis of radionuclides in the interlayer region affected by specific conditions, prevailing in the context of the radioactive waste management is fundamental to understand and correctly estimate the retardation of the radionuclide cations in the clay barrier.

2. The Role of Large Facilities

Synchrotron, X-ray and IR-radiation is increasingly used to characterise complex environmental materials, in particular when those materials are in unusually extreme environments (reactive medium, biological growth medium, high pressure and salinity). Nanoscience asks for a fundamental understanding of the interaction between particles and liquids (or gases) at the various length scales. This task requires the development/use of advanced analytical technologies.

With increasingly tighter regulations, environmental sustainability will demand clever design. As the future challenges lie in the nm regime, it is imperative that environmental science and technology should have the appropriate analytical tools available to explore the nanostructure of contaminant and

engineered decontamination processes.

While electron microscopy related observations often involve highly specific sample treatments prior to “post mortem” structure visualisation and the risk for radiation damage, more recently developed experimental tools, such as synchrotron radiation and neutrons in combination with advanced microscopy tools (STM/AFM), will revolutionise the future progress in environmental sciences. Highly promising developments are in:

- X-ray and neutron reflectivity for probing surfaces and interfaces
- X-ray microtomography to achieve a 3-D map of the porosity in natural and engineered materials
- Elemental and redox mapping at the micron scale (μ -XRF, c-EXAFS and μ -XANES) will allow visualising the complexity of any (atmospheric, soil, plant, microbial mat or sediment) particle system and their interactions with nanoparticles
- Contrast variation, either by isotopic substitution in neutron scattering experiments to probe the local environment, particularly the local water structure around a given atom, or by energy scattering to map the presence of a given element
- Small angle neutron scattering to see within large structures fluctuations of density at the μm size level
- 3-axis quasi-elastic scattering to follow fluctuation of density in water layers
- Neutron and spin-echo time of flight, to look at diffusion at the ps or ns.

Apart from the high potential to visualise structures with nanometer dimensions, there is the unique potential of synchrotron radiation and neutron techniques to observe:

- Structural changes in real-time (typically down to ms), under environmental-like “stopped-flow” conditions (water, flow, pressure, temperature) and in a non-destructive mode
- Redox change in the same conditions, e.g. during oxidation of organic molecules.

Nano-size objects are usually poorly crystalline and the techniques to analyse the structure of liquid and amorphous systems are applied. Specially used is the technique

known as PDF, for Partial Distribution Function, which analyse the distribution of distances in a short range of tenths of nanometers.

As an example, several large facilities techniques (neutron diffraction with isotopic substitution, EXAFS, QENS and molecular dynamics) were used in the study of the coordination of the Sm^{3+} in the interlayer of hydrated synthetic montmorillonite and hectorite. The neutron diffraction results indicate that not all O atoms in the first coordination shell of the Sm^{3+} belong to water molecules, supporting the formation of the Sm^{3+} inner-sphere complex. On the other hand, the other techniques suggest that the adsorbed Sm^{3+} cations form outer-sphere complexes with the clay surface. The hypothesis making compatible all results is that different Sm species are adsorbed in the clay interlayer: a part of Sm is in the Sm^{3+} cationic form, forming outer-sphere adsorption complexes, another part is hydrolyzed and present in the interlayer space as $\text{Sm}(\text{OH})_2^+$, $\text{Sm}(\text{OH})_2^+$, or $\text{Sm}(\text{OH})_3^0$ species. The latter are more hydrophobic than Sm^{3+} cations and can be dehydrated and are able to stick to the clay surface.

3. Short Range Order in Clay Minerals

Smectite clay minerals such as montmorillonite (Mnt) consist of layers comprised of a sheet of octahedrally coordinated cations (Mg^{2+} or Al^{3+}) sandwiched between sheets of tetrahedral cations, as Si^{4+} . The clay sheets acquire net negative charge when octahedral and/or tetrahedral cations are substituted by species of lower valence.

This negative charge is balanced by interlayer cations. The structure, chemical composition, exchangeable ion type and small crystal size of smectite clays are responsible for several unique properties, including a high cation exchange capacity, a large chemically active surface area that make them very useful for large number of applications. Clay minerals have been selected as the most suitable buffer material for high-level radioactive waste repositories. The buffer material is expected to retard the migration of the radio-

nuclides in the case of corrosion of the waste package material. The trivalent cations represent an important part of the radionuclides that could potentially be released from radioactive waste repositories and then migrate through the clay barrier. The lanthanides are of interest because they are often taken as a chemical analogue for trivalent actinides (*Bradbury 2002*).

The coordination of the Sm^{3+} cation in the clay interlayer is studied using techniques commonly used in the study of non-crystalline materials as: Neutron Diffraction (ND) with Isotopic Substitution (NDIS), Extended X-ray Absorption Fine Structure (EXAFS) spectroscopy, Quasi-Elastic Neutron Scattering (QENS), and Molecular Dynamics (MD) simulations (*Sobolev et al., 2011*). The standard ND experiments give an overall view of the structure of the bulk. In the absence of a periodic pattern repeated along the whole system, what is obtained from a diffraction experiment is the ensemble of correlation functions for all pairs of atomic species present. The same is valid for the synchrotron X-ray diffraction (XRD), where the only difference is the weight of each correlation function in the total scattering.

Different isotopes have diverse neutron scattering power, then isotopes with good scattering contrast can substitute some atomic species. Performing two experiments with two different isotopes of a given atom, and doing the corresponding difference, the correlation functions centred in that particular atom are obtained, giving a partial information about the environment of that atom in the system (*Cuello 2008*). The same can be done for synchrotron radiation, but changing the characteristics of the incident radiation. The X-ray beam can be tuned at the energy corresponding to an absorption edge of a given atom and the correlation functions involving this atom can be obtained (*Koningsberger 1998*). There exist an equivalent technique for neutrons, anomalous diffraction (*Wright 2007*), but it can be only used for atoms with low-energy absorption resonances, i.e. only few atoms, inter alia the Sm (*Cole 2007*).

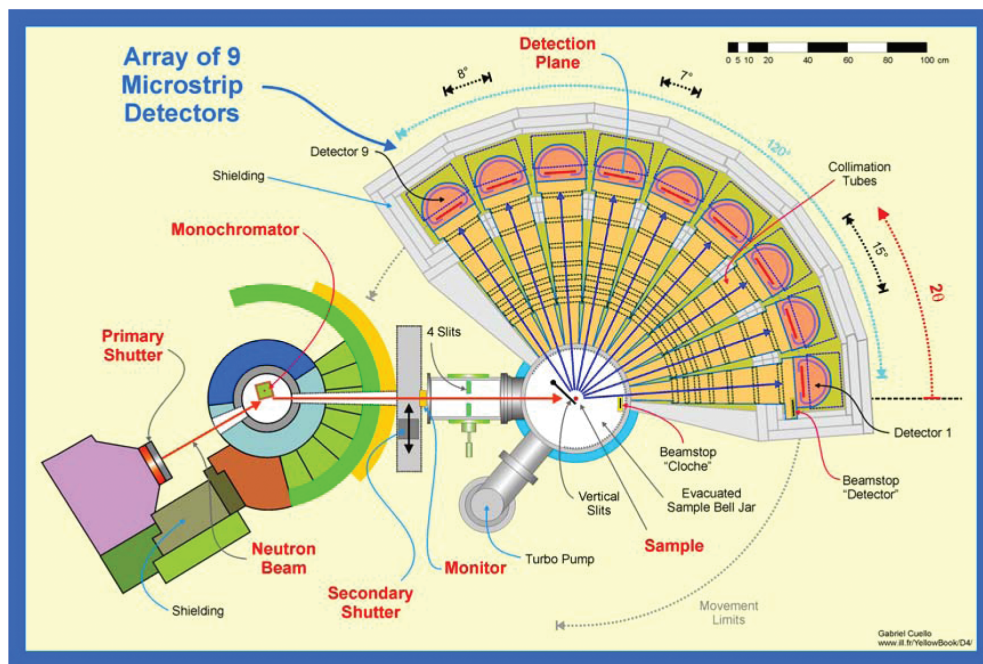


figure 1. Experimental layout of the two-axis neutron diffractometer D4 at the Institute Laue Langevin, Grenoble, France.

The QENS experiments determine very low energy ex-changes between neutrons and the system (below meV) allowing the observation of diffusion movements (Bée 1988). This technique is particularly useful to see the mobility of water, thanks to the very strong scattering power of hydrogen and oxygen for neutrons. Finally, the MD simulations are necessary because with the experimental techniques only a partial view of a very complex problem is obtained. The numerical simulations allow the construction of reasonable models describing the experimental observations, with the drawback that in some cases they can conduct to different solutions compatible with the experiments. But in most of the cases, even if the unicity of their results is not guaranteed, the MD simulation is a fundamental tool in the interpretation of the experimental results in disordered or low-crystalline materials.

The NDIS experiments with Sm-montmorillonite samples (Sobolev 2008a, 2008b) showed that the number of hydrogen atoms $N_H = 5.5 \pm 2.0$ in the first coordination shell of Sm^{3+} is equal or even slightly smaller than those of oxygen

atoms $N_O = 7.5 \pm 1.0$. This means that not all these O atoms belong to water molecules, and that the Sm^{3+} ion binds to the clay surface via O siloxane atoms (inner-sphere adsorption complex). This result is very close to those obtained earlier for Yb^{3+} and Nd^{3+} (Pitteloud 2003), though the sample preparation methods and sample mineralogy differ for the two studies. For our QENS experiment (Sobolev 2009), we used another swelling clay, synthetic hectorite, in which the structural OH groups were replaced by F atoms, making it possible to explore subtle effects of hydration that, in the case of montmorillonite, are hidden under the strong elastic peak originated from the clay structural hydrogen atoms. Hectorite is similar to montmorillonite, it is also a swelling clay with octahedral substitutions and a structural charge very close to that of montmorillonite. The QENS experiment revealed a strong interaction between water and Sm^{3+} interlayer cations that can be considered as an indication of formation of outer-sphere complexes (Sobolev 2009).

4. Experimental

A synthetic fluorated hectorite sample

(Sobolev 2009) was used for the ND experiments. The detailed samples preparation procedure was presented elsewhere (Sobolev 2008a, 2008b, 2009), and the compositions of the samples are given by the simplified unit cell formula:

$^{152}\text{Sm}_{0.28}(\text{Mg}_{5.2}\text{Li}_{0.8})(\text{Si}_8\text{O}_{20}\text{F}_4) + 9.1 \text{ D}_2\text{O}$; for the ^{152}Sm isotope, and the same formula for the other isotope, just replacing ^{152}Sm by ^{154}Sm .

The ND measurements were performed at the D4C diffractometer (Fischer 2002), with an incident wavelength of 0.7 Å (see Fig. 1). The samples were filled in a 7.0 mm outer diameter cylindrical vanadium container, and the loaded sample container was weighed before and after each measurement to verify that no dehydration had occurred. Diffraction patterns were measured at room temperature (298 K) for each sample, as well as for the empty sample container, the instrument background and a 6 mm diameter vanadium rod. The data were corrected for background, empty container, attenuation, and multiple scattering, and normalized to the scattering from vanadium, taking into account the energy dependent neutron scattering cross sections of water (Cuello 2008).

The EXAFS experiments were performed at the DUBBLE beamline (BM26A, ESRF) (see Fig. 2). Sm-L_{III}-edge spectra were recorded as a func-

tion of energy over the range 6.47–7.31 keV defined by the stepping of a Si(111) double-crystal monochromator. Measurements were performed in fluorescence mode. The following Sm–Montmorillonite samples with different water content were measured at room temperature: aqueous solution of Sm(III) (0.05 M), wet paste, powder prepared in a 70% humid atmosphere (two layers hydrate), and powder dried at 150°C during 9 h.

The interlayer basal spacing (BS) of the powder samples was determined by X-ray diffraction. For the powder sample, the BS = 15.85 Å corresponds to a 2-layer hydrate. The sample dried in the oven (BS = 13.63 Å) was found in a transition state between 2- and 1-layer hydrate, being closer to the one hydrate state. In this case, the Sm³⁺ cation is expected to be in direct contact with the clay surface. An experiment with the dry powder sample should test the ability of the EXAFS method to detect such contacts via the observation of second neighbouring clay silicon atoms.

5. Results

In simulations where the starting position of Sm³⁺ was in the middle of the interlayer, Sm³⁺ remained fully hydrated in the middle of the interlayer space during the complete simulation time. The parameters

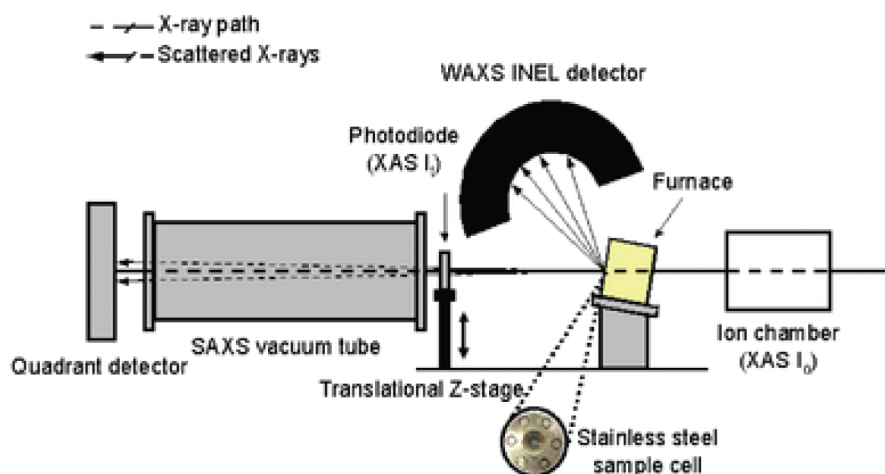


figure 2. Experimental layout of the EXAFS beamline (BM26A) at the European Synchrotron Radiation Facility, Grenoble, France.

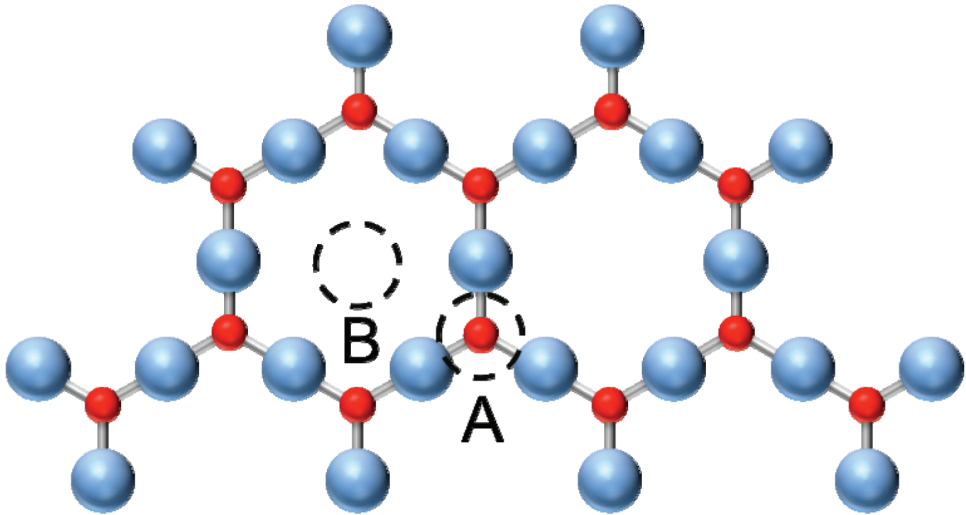


figure 3. Top view of the clay surface, where big and small circles are O and Si, respectively. The two possible locations for the cation on the clay surface are labelled with A and B.

of the Sm^{3+} first coordination shell were found to be identical to those of aqueous solution. In simulations where the starting position of the cations was inside the siloxan cavities (position B, Fig. 3), all 12 cations went to the middle of the interlayer during the first few picoseconds of simulation. The same result was obtained for the

simulation of clay system 2 and starting position A (Fig. 3).

The Sm^{3+} position on the clay surface was stable only in the simulation of clay system 1, where Sm^{3+} was placed in position A (Fig. 3) above Al atoms replacing tetrahedral Si atoms. All 12 cations remained in these posi-

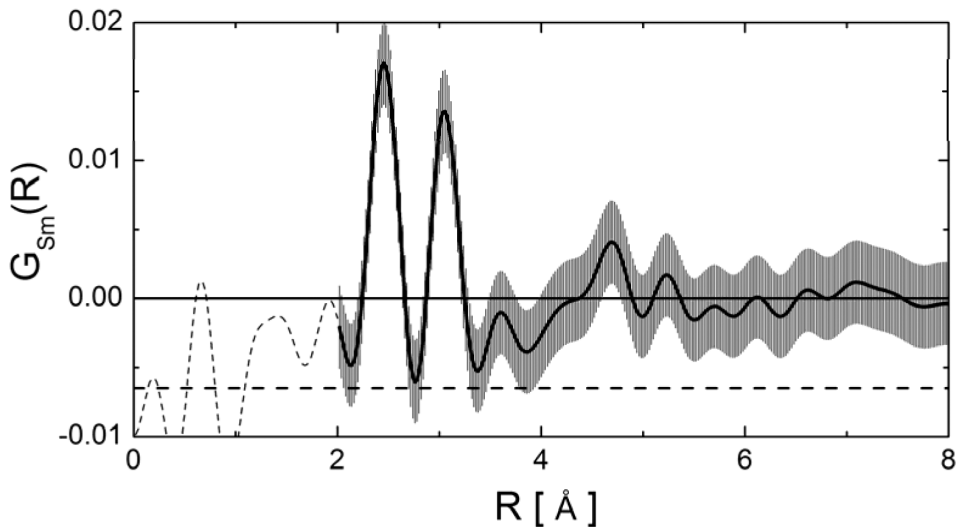


figure 4. Local structure of the Sm^{3+} adsorbed in hectorite, as obtained by neutron diffraction with isotopic substitution experiments. The composite pair distribution function of the D_2O hydrated sample shows two main peaks at 2.5 Å and 3.1 Å, corresponding to Sm-O and Sm-D distances, respectively.

tions during simulation time (800 ps).

The result of the ND experiment with $^{152}\text{Sm}/^{154}\text{Sm}$ isotopic substitution for Sm-Hc sample is shown in Fig. 4, where the $G_{\text{Sm}}(R)$ represents a measure of the probability of finding any atom at a distance R from the Sm atom. The first two peaks of the $G_{\text{Sm}}(R)$ are attributed to the Sm–O and Sm–D correlations. Integration of $G_{\text{Sm}}(R)$ under these peaks gives the number of oxygen and hydrogen atoms around Sm: $N_{\text{O}} = 7.5 \pm 1.0$ and $N_{\text{H}} = 8.5 \pm 2$. Although the observed NH value for Sm-synthetic hectorite is higher than those of the Sm-synthetic montmorillonite samples, it is again much smaller than the expected value for the fully hydrated cation. Therefore, our new result for the Sm-synthetic hectorite reproduces, at least qualitatively, the results obtained before for the Sm-synthetic montmorillonite samples (Sobolev 2008a, 2008b). Moreover, the very similar results, obtained in the cationic exchange experiments for Mnt and Hc, suggest also that parameters of Sm coordination in both these clay minerals are similar.

The EXAFS spectra of Sm^{3+} sorbed to montmorillonite are shown in Fig. 5 along with the Sm^{3+} aqua complex. All samples are dominated by backscattering from the coordinating O

atoms as is evident from the Fourier transform peak at about 2 Å (uncorrected for phase shift). Two smaller peaks follow this main peak at about 3 and 4 Å, also present in the spectrum of the aqua complex, then it can be excluded that they are due to backscattering from atoms at the Mnt surface. They could not be fitted with backscattering Sm atoms, hence the formation of aqueous polymeric species or precipitates can also be excluded. The FEFF calculations showed, that in the tricapped trigonal-prismatic configuration of 9-coordinated, trivalent lanthanoid species, a 3-legged, 12 degenerate multiple scattering paths involving the two different Sm–O distances within the coordination sphere should contribute significantly (7%) to the EXAFS spectra. In fact, this path could be successfully fitted to the Fourier transform peak at about 3 Å, but explaining only half of the peak area. An alternative explanation may be the influence of double-electron excitation features, which are apparent as a small double peak extension of the EXAFS oscillation at 6.3 \AA^{-1} . Since their influence on fitted first shell parameters is negligible for REE^{3+} aqua ions (Ohta 2008), the interpretation of these parameters should not be biased.

The most important conclusion from these EXAFS spectra is that there is no significant

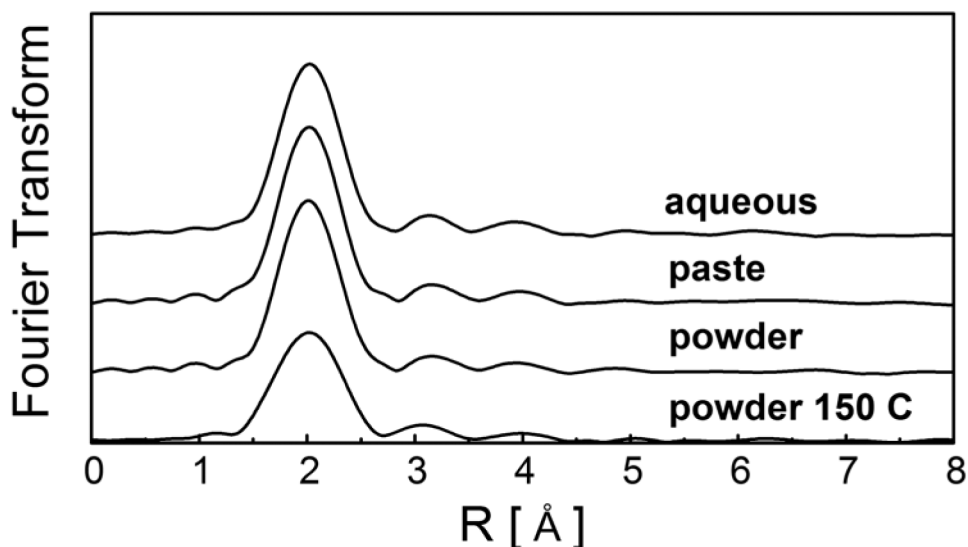


figure 5. Fourier transforms of the Sm-LIII, as obtained from the EXAFS experiments.

influence of montmorillonite surface atoms, supporting the idea that the sorption complexes are strictly outer-sphere. On the other hand, the contacts of Sm^{3+} cations with clay surface should be very frequent in the case of the 150°C sample, which has only one water layer left in the interlayer space. These contacts, however, are not reflected in the EXAFS spectra, probably because of a high positional disorder and destructive interference of backscattering electron waves. Therefore, in general we cannot rule out completely the possibility of such contacts for the others Sm- montmorillonite samples.

The EXAFS spectra were further investigated by shell fitting applying 2 schemes. In a first approach, only one Sm–O shell was fitted, which allowed to keep the coordination number (CN) floating. Because of the high disorder (mean square displacement of 0.01 Å²) the asymmetry was taken into account by fitting a 3rd cumulant. This approach gave meaningful results except for the last sample (powder 150°C), where the cumulant value must be set to zero. With the only exception of 150°C sample, the CN was 9, being the distance of 2.48 ± 0.01 Å in line with a 9-fold coordination (Ohta 2008).

In a second approach, the tricapped trigonal-prismatic structure of the O coordination was taken into account (Persson 2008). Since single-shell CN were 9 for all except for one sample, two-shell CN were fixed to 3 and 6 for the shorter and longer Sm–O distances, respectively. For the 150°C sample, these CN were freed step by step, achieving a stable fit without CN constraints. The CN of the longer Sm–O distance remained at 6, hence the prismatic structure was largely maintained, while the CN of the shorter Sm–O distance decreased to 1.6.

5. Discussion

The ND experiments showed that the number of H atoms NH in the first coordination shell of interlayer Sm^{3+} , in comparison with the number of O atoms N_O , is much smaller than the value expected for the fully hydrated cation ($\text{NH} = 2N_O$). This result is reproducible for different clay minerals, synthe-

tic montmorillonite (Sobolev 2008a, 2008b) and hectorite, and it is very close to the result obtained earlier for Yb^{3+} and Nd^{3+} adsorbed on Wyoming montmorillonite (Piteloud 2003). The simplest explanation for this deficit of H atoms is that the Sm^{3+} cation forms an inner-sphere complex with the clay surface. However, this is contradicted by the EXAFS spectra, which did not show any difference between Sm-montmorillonite wet paste, two-layer hydrate and aqueous solution supporting that the sorption complexes are outer-sphere. The absence of the signal from the Si atoms located beyond the clay O could mean that the adsorbed Sm has no any preferable position on the clay surface, so that the distribution of the Sm–Si distances is very broad. Therefore, even if we admit the possibility of an inner-sphere complex, the interaction Sm^{3+} –clay surface would remain weak.

However, the formation of an inner-sphere complex is not typical for cations strongly interacting with water molecules, especially if the cations adsorbed in the interlayer of clay minerals having only octahedral isomorphic substitutions, such as synthetic montmorillonite and hectorite that we used for our experiments. Therefore, in order to stick to the clay surface, the Sm^{3+} should interact weakly with water molecules. This is only possible if Sm^{3+} is hydrolyzed and present in the clay interlayer as $\text{Sm}(\text{OH})^{2+}$, $\text{Sm}(\text{OH})_2^+$ or $\text{Sm}(\text{OH})_3^0$ species. These species being more hydrophobic than trivalent cations can be dehydrated and can stick to the clay surface. This hypothesis, however, is not supported by the results of the QENS experiments (Sobolev 2009) indicating a strong interaction between water molecules and interlayer Sm^{3+} cations. It is worth mentioning that our X-ray data and water content analysis of the samples indicate a double layer of water molecules in the interlayer space (whereas one might expect a collapse to lower interlayer water content, if Sm is bound to the clay surface and dehydrated) which is also an evidence that Sm^{3+} cations in the clay interlayer (at least some of them) form outer-sphere adsorption complexes.

It should be noted that only the NDIS allowed direct observation of water coordination to the Sm^{3+} cation, since only neutrons can observe hydrogen atoms. The NDIS results point to a deficit of water molecules around Sm^{3+} . The results obtained with the EXAFS and QENS provide an indirect evidence for the outer sphere complexation, but they cannot rule out the presence of inner sphere complexes. The cationic exchange experiments have shown that not all adsorbed Sm in the clay interlayer is exchangeable and therefore persists in the interlayer in the cationic form.

The deficit of H observed in diffraction experiments is compatible with the MD, EXAFS, and QENS results (supporting the Sm^{3+} outer-sphere adsorption complex), if two kinds of complexes are present: outer-sphere and inner-sphere coexist in the clay interlayer. The explanation proposed for this finding is that there are different Sm species adsorbed in the clay interlayer: a part of Sm is in the Sm^{3+} cationic form, forming outer-sphere adsorption complexes, another part is hydrolyzed and present in the clay interlayer as $\text{Sm}(\text{OH})^{2+}$, $\text{Sm}(\text{OH})_2^+$, or $\text{Sm}(\text{OH})_3^0$ species. The precipitation version is not supported by the EXAFS results, since no indication of the Sm peak was found at longer distances. For a correct interpretation of our experimental results one should take into account the fact that the number of O atoms found in the first coordination shell of the interlayer Sm is rather high: 7.5 ± 1.0 (NDIS) and 9.2 ± 0.5 (EXAFS). Therefore, if we assume that some of the adsorbed Sm present in the interlayer space are hydrolyzed species $\text{Sm}(\text{OH})^{2+}$, $\text{Sm}(\text{OH})_2^+$, or $\text{Sm}(\text{OH})_3^0$, they are necessarily in contact with the O atoms from the clay. These hydrolyzed species being more hydrophobic than trivalent cations, they can be dehydrated and stick to the clay surface.

6. Conclusions

Because environmental research is a multidisciplinary field, a single effort or centre cannot address all the key challenges. It is at the nano-level that physical changes and interactions with contaminants determine the designed decontamination process effi-

ciency. Therefore, an integrated and multidisciplinary approach of key problems in environmental research and industry is required.

The environment can only be studied successfully when research is to be extended from structural and compositional studies to studies of environmental dynamics. This work will involve time-resolved structural studies by means of small-angle scattering, diffraction, imaging and tomography. Mostly, parallel use of different techniques and the application of complicated external conditions based on concentration and hydraulic potential gradients will be necessary.

Understanding the fundamental processes in nuclear waste repositories with unprecedented detail is a key requirement for assessing a final solution for nuclear waste treatment, and ultimately for the acceptability of nuclear energy by society.

Still open questions are related to nanoscale processes, including the behaviour of ceramics and other nuclear waste forms under self-irradiation, redox and dissolution processes at waste container/water interfaces, the transport of dissolved and colloidal radionuclides in natural geomeia characterised by chemical micro-domains, and bio-molecular interfaces controlling transfer of radionuclides to microorganisms, plants, animals and man.

Investigation of these nanoscale processes requires a range of synchrotron and neutron techniques with μm to nm resolution. Note that moving from the state-of-the-art (15 nm for few techniques) to below 7 nm will have a great impact and then from there down to 2 nm and possibly to the sub-nanometre level once again. At the same time, larger scales up to the mm and dm range should not be neglected in order to tie in (chemical) molecular processes with (physical) transport processes.

These techniques have to be accessible for highly radioactive and radiotoxic samples, including spent nuclear fuel and samples containing radionuclides with proliferation concerns. This requires beam lines and sample

preparation labs with the respective safety installations, as well as the appropriate permissions and administrative regulations. Note that the spent nuclear fuel problem is an essential and driving part of the entire nuclear fuel cycle, but is barely accessible with current restrictions.

These techniques have to be integrated with theory, simulation, and computational approaches and be linked to the macroscopic approach in order to ensure the consistency between the various scales.

The research covers a wide range of different scientific fields, including nuclear chemistry and material sciences for the study of waste matrices, all aspects of environmental sciences including colloid and geochemistry, hydrology and soil physics and chemistry, several aspects of life sciences including biophysics and chemistry, microbiology, plant physiology and medicine, beamline development and theory. Strong collaborative efforts between scientists of these different fields are essential for a multi-disciplinary approach.

To make best use of synergies, this effort has to implement, utilise and build on already existing research infrastructures, e.g. national and international nuclear facilities and universities, as well as large scale facilities

These conclusions should at least materialise in:

- Instrument development at large-scale facilities for multi-technique analysis, in real-time, under conditions simulating appropriate engineering strategies, dedicated to decontamination problems and waste management
- A network of interdisciplinary researchers involved in the study of the interplay between micro- and nano-structure made of nanoparticles and nanotubes, cells and upper organisms
- Enhanced cooperation between environmental experts from the waste and water industry, academia, and the scientists at the large scale facilities
- High priority on environmental research, also in the allocation of beam line access at research facilities.

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