Ultra sensitive speciation of radionuclides by laser spectroscopy

Clemens Walther
Mobilization and immobilization of radionuclides

**Introduction**

**Mobilization:**
- solubility
- redox reactions
- complexation
- colloids

**Immobilization:**
- corrosion
- secondary phases
- sorption
- precipitation

**Backfill-material**

**Hostrock**
Reactions of Radionuclides on Molecular Scale

Polymer: \( \text{eg.: } M_x(\text{OH})_y^{q+} \)

Aquifer → Solvate und colloidal species

Nucleation/ Sorption

Dissolution/ Desorption

Coagulation/ Flocculation

Intrinsic Colloids

Sorption, Incorporation

Resuspension

Sedimentation

Transport

Spent fuel

Reactions of Radionuclides on Molecular Scale

Pseudo-Colloids
Reactions of Radionuclides on Molecular Scale

Polymer: 
eg.: \( M_x(OH)_y^{q+} \)

Aquifer

Solve und colloidal species

Nucleation/ 
Sorption

Dissolution/ 
Desorption

Coagulation/ 
Flocculation

Pseudo-Colloids

Transport

Spent fuel

Sorption, 
Incorporation

Ionic 
Species

Intrinsic 
Colloids

Sorption, 
Incorporation

Polymer:

\( M_x(OH)_y^{q+} \)

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Colloids

Sorption, 
Incorporation

Polymer:

\( M_x(OH)_y^{q+} \)
Principle of Time Resolved Laser Fluorescence Spectroscopy

Light source

Sample

Detector

TRLFS
Time Resolved Laser Fluorescence Spectroscopy

LIBD
Laser Induced Breakdown Detection
Applicable to many Lanthanides and Actinides: 5f-5f Electron Transitions
Principle of Time Resolved Laser Fluorescence Spectroscopy

Monochromatic light source → Sample → Detector

TRLFS
Time Resolved Laser Fluorescence Spectroscopy

LIBD
Laser Induced Breakdown Detection
The case of Cm(III): Absorption bands

Energy levels of Cm(III)

Optical Spectrum

- 375.5
- 381.3
- 396.0
- 593.8

(Wavelength (x10^{-3} cm^{-1})

Energylevels

- H
- G
- F
- A
- Z

Fluoresence

- Relaxation
- Lifetime ≤ 10^{-3} s

Cm^{3+}\text{aq} : 593.8 \text{ nm}

Principle of Time Resolved Laser Fluorescence Spectroscopy

Monochromatic light source -> Sample -> Spectrometer -> CCD Array Detector

TRLFS: Time Resolved Laser Fluorescence Spectroscopy

LIBD: Laser Induced Breakdown Detection
The Signal: Fluorescence Bathochromic Shift of Cm(III)

Normalized Cm(III) Fluorescence Emission

Cm (III) Aquo Ion
Cm(III) / Calcite Sorption
Cm(III) Incorporation

Wavelength / nm

593.8 nm
607.5 nm
618.0 nm

Stumpf, Habilitation FZK 2007
 Principle of Time Resolved Laser Fluorescence Spectroscopy

**Pulsed Monochromatic light source**

- **Sample**
- **CCD Array Detector**
- **Gated Intensifier**
- **Spectrometer**
- **Pulser/Delay Gate**

**TLRFLS**: Time Resolved Laser Fluorescence Spectroscopy

**LIBD**: Laser Induced Breakdown Detection

**Laser Photoacoustic Spectroscopy**
**Time Resolved** Laser Fluorescence Spectroscopy

**Lifetime:**
N(H$_2$O) in first coordination sphere

- **Excitation:** 396.6 nm
- **Emission:** $\lambda = 593.8$ nm
- **Lifetime:** 1300 $\mu$s

**Cm$^{3+}$**

Nonradiative relaxation

$A = ^6D_{7/2}$

$Z = ^8S_{7/2}$

H$_2$O

"Quench"
**Time Resolved Spectra**

- **TRLFS**: Time Resolved Laser Fluorescence Spectroscopy
- **LIBD**: Laser Induced Breakdown Detection

**Figure Description**

- **Fluorescence Emission Intensity**
  - **Wavelength / nm**: 580, 600, 620
  - **pH 5.45**
  - **Time / μs**: 0, 100, 200, 300, 400

**Graph Details**

- **Lifetime**
  - $t_1 = 68 \pm 3 \, \mu s$
  - $t_2 = 123 \pm 10 \, \mu s$

**Equation**

- $nH_2O = 0.65 \, K_{obs} \, (Cm)^{-0.88}$
**Time Resolved Spectra**

**pH 5.45**

- **Fluorescence Emission Intensity**
  - **1 µs**
  - **100 µs**

- **Wavelength / nm**
  - 580
  - 600
  - 620

- **Lifetime**
  - $t_1 = 68 \pm 3 \mu s$
  - $t_2 = 123 \pm 10 \mu s$

- **In Fluorescence Emission Intensity**

- **Time / µs**
  - 0
  - 100
  - 200
  - 300
  - 400

- **nH₂O = 0.65 K_{obs} (Cm)^{-0.88}**
Time Resolved Spectra

TRLFS
Time Resolved Laser Fluorescence Spectroscopy

LIBD
Laser Induced Breakdown Detection

Fluorescence Emission Intensity

pH 5.45

1 µs
100 µs
150 µs

Wavelength / nm

580 600 620

In Fluorescence Emission Intensity

Time / µs

0 100 200 300 400

Lifetime

\( t_1 \) 68 +/- 3 µs
\( t_2 \) 123 +/- 10 µs

\( nH_2O = 0.65 K_{obs} (Cm) - 0.88 \)

Trivalent actinide - bentonite interaction studied by TRLFS

Inner-sphere complex (e.g. Cm(III) - γ-alumina, pH 9)

Mineralization, Incorporation (e.g. Cm(III) - silica, pH 9)

Outer-sphere complex (e.g. Cm(III) - smectite, pH <5)

peak maximum: 593.8 nm; lifetime: $\tau = 67$ µs

Irreversible?

slowly reversible

rapidly reversible

peak maximum: 593.8 nm; lifetime: $\tau = 114 \pm 6$ µs

peak maximum: 580 - 620 nm

Mineralization, Incorporation (e.g. Cm(III) - silica, pH 9)

Ca-smectite (250 µg/l)

pH = 9.2

(τ = 110 µs)

bentonite (20 mg/l)

pH = 9.2

(τ = 102 ± 4 µs)

groundwater

pH = 9.2

(τ = 67 µs)

residual: (Cm(III)-organics?)

scaled Cm(III)-smectite spectrum

Trivalent actinide - bentonite interaction studied by TRLFS

TRLFS
Time Resolved Laser Fluorescence Spectroscopy

Liberal, Photoacoustic Spectroscopy

LIBD
Laser Induced Breakdown Detection

ACS ENVR Philadelphia Aug 19-23 2012
Clemens Walther
Leibniz University Hanover
Complexation by Organic Molecules

Repository

HYDROSTRATIGRAFISCHER SCHNITT

Legende

Tertiär
- Hamburg Ton: Miozän
- Miozän und Oligozän
- Sande
- Oligozän und Eozän Tone

Quartär
- Holstein Ton
- Lauenburger Ton
- Sand
- Schluft, Gestebsbereich

Zechstein
- Hutgstein
- Galtz

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Indirect Excitation The case of Cm/Humic Acid

Fluorescence

Cm\textsuperscript{3+}  

396.6 nm  

\(6\text{I}_{9/2}\)  

396.6 nm  

\(6\text{D}_{7/2}\)  

366 nm  

\(6\text{D}_{7/2}\)  

Emission

\(8\text{S}_{7/2}\)  

\(8\text{S}_{7/2}\)

Energy Transfers?

Non-radiative Relaxation

\(k_1 \sim 10^3\text{ to } 10^4 \text{ s}^{-1}\)

\(k_2 \sim 10^8 \text{ s}^{-1}\)

log fluorescence emission

Time / \(\mu\text{s}\)

0 100 200 300 400 500 600

10\text{e}\) 10\text{e}\)

bi-exponential decay  \(\Rightarrow 2\) species

mono-exponential decay  \(\Rightarrow 1\) species OR 2 or more exchanging species

Fluorescence

Vibrational Quenching

\(\nu_{\text{OH}}\)  

5  

4

3  

2

1

0

\(\nu_{\text{OD}}\)  

7  

6

5

4

3

2

1

0
Lifetimes in H$_2$O at different pH

- all biexponential
  - $\sim 65 \mu$s
  - $\sim 150 \mu$s
- at pH 3 - 3.5 only small contribution with longer lifetime visible, increasing with increasing pH

Lifetimes in D$_2$O at different pD

- monoexponential behavior,
- but different, decreasing lifetimes!
- Different species for each pD? Unlikely!
- or only two different exchanging species with pD-dependent ratio

Spectroscopy at 77K

TRLFS
Time Resolved Laser Fluorescence Spectroscopy

LIBD
Laser Induced Breakdown Detection

Laser Photoacoustic Spectroscopy
Measurements at 77K

Excitation at 366 nm

monoexponential
lifetime ~ 700μs

biexponential
lifetimes 1085 μs (36%)
440 μs (64%)

Complexation by Humic Acid (HA)

Natural HS: GoHy 573

Reversible Binding

Aggregates

Reactions of Radionuclides on Molecular Scale

Polymer: eg.: $M_x(OH)_y^{q+}$

Aquifer → Solvate und colloidal species

Nucleation/Sorption → Dissolution/Desorption → Sorption

Coagulation/Flocculation

Desorption

Sorption

Resuspension

Sedimentation

Transport

Aquifer to solvent fuel

Sorption, Incorporation

Pseudo-Colloids

Ionic Species

Solvate und colloidal species

Intrinsic Colloids

Spent fuel

Transactions of Radionuclides on Molecular Scale

Pseudo-Colloids
Solids

TRLFS

Acquatic samples/colloids

TEMPERATURE: 10 K - 473 K
Principle of Time Resolved Laser Fluorescence Spectroscopy

**Tunable Pulsed Monochromatic light source**

- Tunable Pulsed Monochromatic light source
- Sample
- Cryostate (4K)
- CCD Array Detector
- Spectrometer
- Gated Intensifier
- Pulser/Delay Gate
Low temperature-TRLFS

Cm: [Y(H₂O)₆]Cl₃·15Crown5

One single species?
Principle of Time Resolved Laser Fluorescence Spectroscopy

**Excitation Spectroscopy**

**Tunable Pulsed Monochromatic light source**

Sample

Spectrometer

CCD Array Detector

Gated Intensifier

Pulser/ Delay Gate

---

**TRLFS**
Time Resolved Laser Fluorescence Spectroscopy

**LIBD**
Laser Induced Breakdown Detection

---

**Clemens Walther**
Leibniz University Hanover
Optical Parametric Amplifier (2.5µm – 210nm)
Groundstate Splitting

\[ T = 15 \text{ K} \]

\[ [\text{Y(H}_2\text{O)}_8]\text{Cl}_3 \cdot 15\text{C}_5 \]

Emission

Excitation

Wavenumber (cm\(^{-1}\))

16760 16770 16780 16790 16800 16810

35 cm\(^{-1}\)

(Crown ether)

\[ Z_1 \]

\[ Z_2 \]

\[ Z_3 \]

\[ Z_4 \]
Low temperature spectroscopy

Cm:\[\text{Y(H}_2\text{O)}_8\text{]}\text{Cl}_3\cdot\text{15Crown5}

One single species

Excitation Spectroscopy at Different Temperatures

[Cm:Y(H₂O)₈]Cl₃(15-crown-5)

Boltzmann Distribution

One single Species!

Low Temperature – Excitation Spectroscopy

[Cm\(^{3+}\):Y(H\(_2\)O\(_9\))(BrO\(_3\))\(_3\)]

Three different sites

- 6P\(_{5/2}\)
- 6D\(_{7/2}\)
- 8S\(_{7/2}\)

- Wavenumber cm\(^{-1}\)
  - 25214 cm\(^{-1}\)
  - 16778 cm\(^{-1}\)
  - 16773 cm\(^{-1}\)
  - 16757 cm\(^{-1}\)
Example: M(III) incorporation into Calcite

Charge compensation

- Three models mainly in discussion:
  - $\text{EuOH}^2+ \leftrightarrow \text{Ca}^{2+}$
  - $2 \text{ Eu}^{3+} + \leftrightarrow 3 \text{ Ca}^{2+}$
  - $\text{Eu}^{3+} + \text{Na}^+ \leftrightarrow 2 \text{ Ca}^{2+}$

<table>
<thead>
<tr>
<th>Cation</th>
<th>Ionic radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Ca}^{2+}$</td>
<td>114 pm</td>
</tr>
<tr>
<td>$\text{Cm}^{3+}$</td>
<td>111 pm</td>
</tr>
<tr>
<td>$\text{Eu}^{3+}$</td>
<td>109 pm</td>
</tr>
<tr>
<td>$\text{Gd}^{3+}$</td>
<td>108 pm</td>
</tr>
<tr>
<td>$\text{Na}^+$</td>
<td>116 pm</td>
</tr>
<tr>
<td>$\text{K}^+$</td>
<td>152 pm</td>
</tr>
</tbody>
</table>
Direct excitation TRLFS: Eu\(^{3+}\)

- Usually excitation to \(^5\)L\(_6\) band in the UV
- Radiationless de-excitation to \(^5\)D\(_0\) state
- Direct excitation \(^7\)F\(_0\) \(\rightarrow\) \(^5\)D\(_0\)
- Both levels **non-degenerate**
- One singlet signal per Eu\(^{3+}\) site
Eu(III) TRLFS

- Coordination symmetry (emission spectrum) and...
- Hydration state (fluorescence lifetime)
**Eu^{3+} TRLFS results**

- **One sorption** and **two incorporation** species found
- Low symmetry incorporation site B
- Symmetric incorporation site C (Ca^{2+} lattice site)
- Identification by lifetimes/ splitting patterns

### Decay Constants

- **Site A**: $k = 2147 \pm 378 \text{ s}^{-1}$
- **Site B**: $k = 277 \pm 34 \text{ s}^{-1}$
- **Site C**: $k = 273 \pm 16 \text{ s}^{-1}$
Structural model: M(III) in Calcite

Two incorporation species

Immobilization

One sorption species

Reversible

Distinction of sorption and incorporation
Characterization of sites
Molecular level understanding

Na⁺ for charge compensation

Am(III) incorporation into calcite

![Graph showing Am(III) and Cm(III) fluorescence spectra with excitation at 497 nm, delay time 570 ns, and gate width 10 ms.](image)

Excitation at 497 nm; delay time 570 ns; gate width 10 ms
Uranyl luminescence term scheme

Uranyl luminescence term scheme

Time-resolved laser fluorescence spectroscopy
Comparison of spectra from sorbed and aqueous uranyl species

Increasing red shift (lower energy): Indication of weakening of the axial U=O bond, (lower stretch frequency)

Stronger interaction between U(VI) and the equatorial ligands

Change in geometry of uranyl moiety

J. Tits et al., submitted
Uranium (IV)

Protactinium (IV): sulfate complexation / hydrolysis

# Limit of Detection

<table>
<thead>
<tr>
<th>Ion</th>
<th>TRLFS</th>
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<tr>
<td>U-(VI)</td>
<td>1E-10 Mol/l</td>
</tr>
<tr>
<td>U-(IV)</td>
<td>&lt;1E-6 Mol/l</td>
</tr>
<tr>
<td>Pa-(IV)</td>
<td>&lt;1E-8 Mol/l</td>
</tr>
<tr>
<td>Am-(III)</td>
<td>1E-9 Mol/l</td>
</tr>
<tr>
<td>Cm-(III)</td>
<td>2E-13 Mol/l</td>
</tr>
<tr>
<td>Nd-(III)</td>
<td>3E-7 Mol/l</td>
</tr>
</tbody>
</table>

Speciation typ. at 100x higher concentrations
Speciation of Oxidation states of Plutonium

Pu(IV) in 0.5 M HCl

PuO$_2^{2+}$ in 0.1 M HClO$_4$

Pu$^{3+}$ in 1 M HClO$_4$

Laser Photoacoustic Spectroscopy
Laser Photoacoustic Spectroscopy (LPAS)

*Tunable Pulsed*  
Monochromatic light source

**Sample**

Piezo "Microphone"


**Ion specific absorption**

*Generation of heat by non-radiative relaxation*

**Volume expansion**

*Generation and propagation of acoustic wave*

**Detection of acoustic wave by piezoelectric transducer**
LPAS Signal linear with absorptivity and concentration

[Graph showing LPAS Signal (µV/mJ) vs. Concentration (mol/L) for different [Pu(IV)] concentrations in 1M HCl. The graph includes a linear fit with slope 1.01 ± 0.02 and LOD: 10⁻⁷ mol/L.]

J. Yun, unpublished data
Disproportionation (LPAS study)

pH 1.2, $[\text{Pu}]_{\text{tot}} = 3.15 \times 10^{-5}$ M

Pu(IV)
-8.0E-6 M

Pu(III)
+8.7E-6 M

LPAS Signal (µV/mJ)

Wavelength (nm)

Pu(IV)
Pu(III)

J. Yun, unpublished data

Laser Photoacoustic Spectroscopy

TRLFS
Time Resolved Laser Fluorescence Spectroscopy

LIBD
Laser Induced Breakdown Detection

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Influence of light scattering on the UV-Vis spectra

Pr(III) in 0.7 M HNO₃

Pr(III) with colloidal suspension

J.Yun, unpublished data
No Influence of light scattering on the LPAS spectra

[Graph showing LPAS signal (µV/mJ) vs. Wavelength (nm) with data points for different concentrations of Pr(III) and their influence on LPAS spectra with PSP (100nm and 500ppb).]

J. Yun, unpublished data
### Limit of Detection

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Speciation typ. at 100x higher concentrations
TRLFS
Time Resolved Laser Fluorescence Spectroscopy

LIBD
Laser Induced Breakdown Detection

Laser Photoacoustic Spectroscopy
Reactions of Radionuclides on Molecular Scale

Aquifer ➔ Solvate und colloidal species

Spent fuel

Polymer: \( \text{eg.: M}_x(\text{OH})_y^{q+} \)

Nucleation/Sorption ➔ Desorption/Dissolution

Coagulation/Flocculation ➔ Transport

Pseudo-Colloids

Intrinsic Colloids

Ionic Species

Intrinsic Colloids

Polymer: eg.: \( \text{M}_x(\text{OH})_y^{q+} \)

Desorption Sorption

Desorption Sorption

Resuspension Sedimentation

Transport

Laser Photoacoustic Spectroscopy

Laser Induced Breakdown Detection

Time Resolved Laser Fluorescence Spectroscopy

TRLFS

LIBD

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Laser-Induced Breakdown Detection

TRLFS
Time Resolved Laser Fluorescence Spectroscopy

LIBD
Laser Induced Breakdown Detection

Laser Photoacoustic Spectroscopy

CCD Camera
Quartz Cell
Colloid-Suspension
Laser Beam
Lens
Shock Wave
Acoustic Detection

Laser-Induced Breakdown Detection

$P_{\text{solid}} < P_{\text{liquid}}$
Selective Ignition on colloids

pH increase by Coulometric Titration

pH increase → lower solubility → colloid formation

Solubility of amorphous Zr(OH)$_4$
Pu(IV) Colloids

Pu(OH)₄(am)

\[ \log K_{sp}^{\circ} = -58.5 \pm 0.7 \]
(Neck, Kim 2001)

PuO₂(cr)

\[ \log K_{sp}^{\circ} = -64.0 \pm 0.5 \]
(thermochem. value, NEA-TDB)

Pu(IV)aq

Pu(V)

Pu(IV)aq + Pu(V)

Pu(IV)c\text{oll}

Pu(IV)aq + Pu(V)

PuIVaq

PuIVcoll

Pu(V)

\[ \log [\text{Pu}] = -10.4 \pm 0.5 \]
(p.w. (I = 0.1 M)

PuIVaq + Pu(V)

PuIVaq + Pu(V)

PuIVaq

PuIVcoll

Pu(V)

\[ \log [\text{Pu}] = -8.3 \pm 1.0 \]

PuIVaq + Pu(V)

PuIVaq + Pu(V)

PuIVaq

PuIVcoll

Pu(V)

\[ \log [\text{Pu}] = -10.4 \pm 0.5 \]

PuIVaq + Pu(V)

PuIVaq + Pu(V)

PuIVaq

PuIVcoll

Pu(V)

\[ \log [\text{Pu}] = -8.3 \pm 1.0 \]

PuIVaq + Pu(V)

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PuIVaq

PuIVcoll

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PuIVaq + Pu(V)

PuIVaq

PuIVcoll

Pu(V)

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PuIVaq + Pu(V)

PuIVaq + Pu(V)

PuIVaq

PuIVcoll

Pu(V)

\[ \log [\text{Pu}] = -10.4 \pm 0.5 \]

PuIVaq + Pu(V)
Reactions of Radionuclides on Molecular Scale

Polymer: e.g.: $M_x(OH)_y^{q+}$

Intrinsic Colloids

Transport

Spent fuel

Coagulation/ Flocculation

Sorption

Resuspension

Sedimentation

Desorption

Dissolution/ Desorption

Nucleation/ Sorption

Ion Species

Aquifer

Solva te und colloidal species

Pseudo-Colloids

LIBD
Laser Induced Breakdown Detection

TRLFS
Time Resolved Laser Fluorescence Spectroscopy

Leibniz University Hanover

Clemens Walther
Colloids mobile in ground water

**Colloid-mediated transport**

Colloid Transport of Plutonium in the Far-Field of the Mayak Production Association, Russia

Alexander P. Novikov,1 Stephan N. Kulinov,1,2 Satoshi Utsunomiya,1 Rodney C. Curing,2,3 Françoise Hristova,4 Alex Morkovin,5 Sue B. Clark,6 Vladimir Y. Tkachev,7 Boris F. Myasnikov8

*Corresponding author.*

**Lake Kyzyltash, Techa River**

**Tens of meters**

**Centimeters**

**1 km**


Example Colloid Mediated Transport (CRR/CFM)

**If:**
1. Water intrudes
2. Containers corrode
3. Radionuclides leach and
4. Water exits

**Then:**
Transport of Radionuclides
Mobile LIBD for the in-situ colloid detection

Elution through granite fracture

Dipole 3 configuration

BOMI 87.010

150 ml/min

extraction borehole

injection borehole

BOMI 87.008

10 ml/min

Colloid content from mean diameter

Cocktail: Bentonite Colloids
   + Am(III), Pu(IV), Np(V), U(VI)


Inner-sphere complex (e.g. Cm(III) - γ-alumina, pH 9)

slowly reversible
Grimsel Experiment (2008)

Surface from mean diameter

LibD (optical)

Concentration (Metal)

Volumen /ml

Surface (colloids)

Hf (ppb)

Tb (ppb)

Th (ppb)

Dipole 3 configuration

BOMI 87.010

1000 10000 100000 1000000 1E7

1E-3

0,01

0,1

1000 10000 100000 1000000 1E7

100

1000

10000

1E7

10

100

1000

Surface (colloids)
Big colloids travel faster, small ones diffuse into fine fractures

Small Colloids have larger reactive surface relative to their volume

Measurement of Size Dispersion
Direct Observation of Size Dispersion

Grimsel Experiment (2008)

- TRLFS: Time Resolved Laser Fluorescence Spectroscopy
- LIBD: Laser Induced Breakdown Detection
- Laser Photoacoustic Spectroscopy

**Surface from mean diameter**

**Surface from size distribution**

**Concentration (Metal):**
- Hf (ppb)
- Tb (ppb)
- Th (ppb)

**Volumes /ml:**
- LIBD (optical)
- LIBD (s-curve)

**Graph:**
- Volumen /ml vs. Surface (colloids)
- Logarithmic scale on both axes
Natural Systems?

Pareto Distribution

\[
dN/dD \propto D^{-3}
\]

\[
dN/coll / d ml nm
\]

Degueule, Appl. Geochem. 11, 677 (1996)
**Example:** Surface Water (Lake Brienz / CH)

Exceptionally high turbidity due to inorganic colloids downstream of hydro-power plant responsible?


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*IRS*
## Summary

<table>
<thead>
<tr>
<th></th>
<th>TRLFS</th>
<th>LPAS</th>
<th>LIBD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Information</strong></td>
<td>Chemical Speciation of fluorescing Probes: Cm(III) Eu(III) U(VI) Gd(III) Pa(IV) U(IV) Ln(III)</td>
<td>Identification of solution complexes an oxidation states. Absolute concentration</td>
<td>Colloid size distribution 10-1000nm inorganic colloids</td>
</tr>
<tr>
<td><strong>Sample</strong></td>
<td>CN (H₂O), Symmetry 300K averaging 4K site selective</td>
<td>Absorption (not extinction)</td>
<td>Information on ensemble (not single colloid)</td>
</tr>
<tr>
<td><strong>Amount</strong></td>
<td>&gt; 10µg / &gt;1ml</td>
<td>&gt;1ml</td>
<td>&gt;2ml</td>
</tr>
<tr>
<td><strong>Concentration Range</strong></td>
<td>&gt; 1E10 atoms / &gt; 1E-9 M</td>
<td>&gt; 1E-9 M</td>
<td>1E-12 g/g</td>
</tr>
<tr>
<td><strong>Matrix</strong></td>
<td>+no restriction</td>
<td>No restriction</td>
<td>Not too viscous</td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td>0 -500K</td>
<td>273K -350K</td>
<td>273-500K</td>
</tr>
<tr>
<td><strong>Duration of Measurement</strong></td>
<td>Spectra 1-20s Lifetime 1-90 min</td>
<td>10-30min</td>
<td>Mean Size: 3 min Distribution:90min</td>
</tr>
<tr>
<td><strong>Pretreatment</strong></td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td><strong>Commercial Availability</strong></td>
<td>no</td>
<td>no</td>
<td>2013</td>
</tr>
</tbody>
</table>
Thanks ...

M. Altmaier
C. Bitea,
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Questions?