LTSM – Laboratoire tri ionique par les systèmes moléculaires auto-assemblés

Lipophilic Derivatives of AminoPolyCarboxylic Acids as New Extractants for the Fuel Cycle and the Recycling of Non-Radioactive Rare Earth Elements: Context and Examples.

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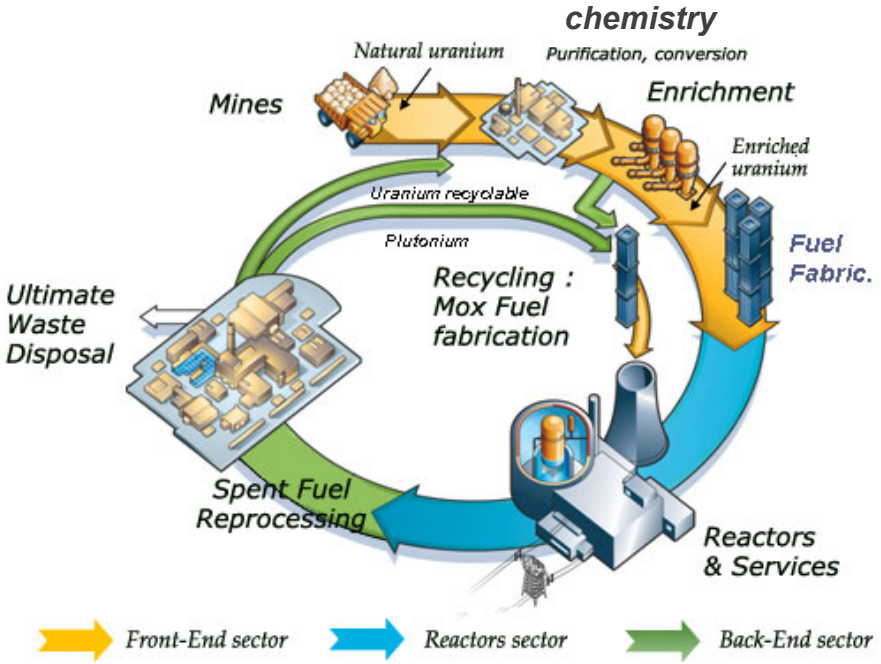
CONTEXT: Liquid-Liquid Extraction (LLE) & Hydrometallurgy of Actinides & Lanthanides

Mining & Recycling of Lanthanides & Actinides

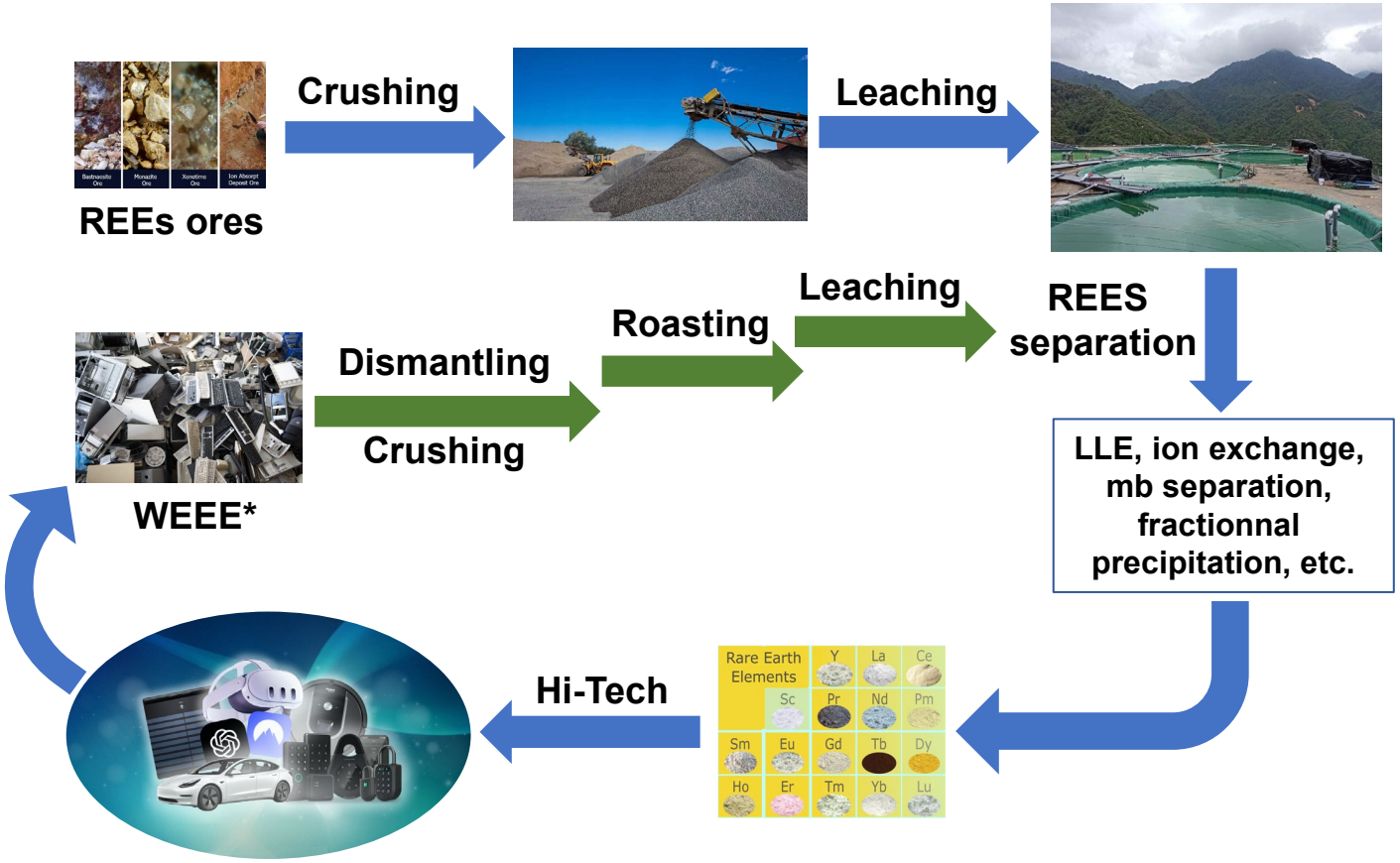
❑ Uranium: the fuel cycle



https://laradioactivite-prod-en.apps.wok3.in2p3.fr/articles/nuclearenergy/fuel_cycle

- LLE processes involved
  - ➢ Front-end
    - ✓ AMEX in sulfuric media
    - ✓ URPHOS in phosphoric media
  - ➢ Back-end
    - ✓ PUREX in nitric media

❑ REEs: extraction and recycling



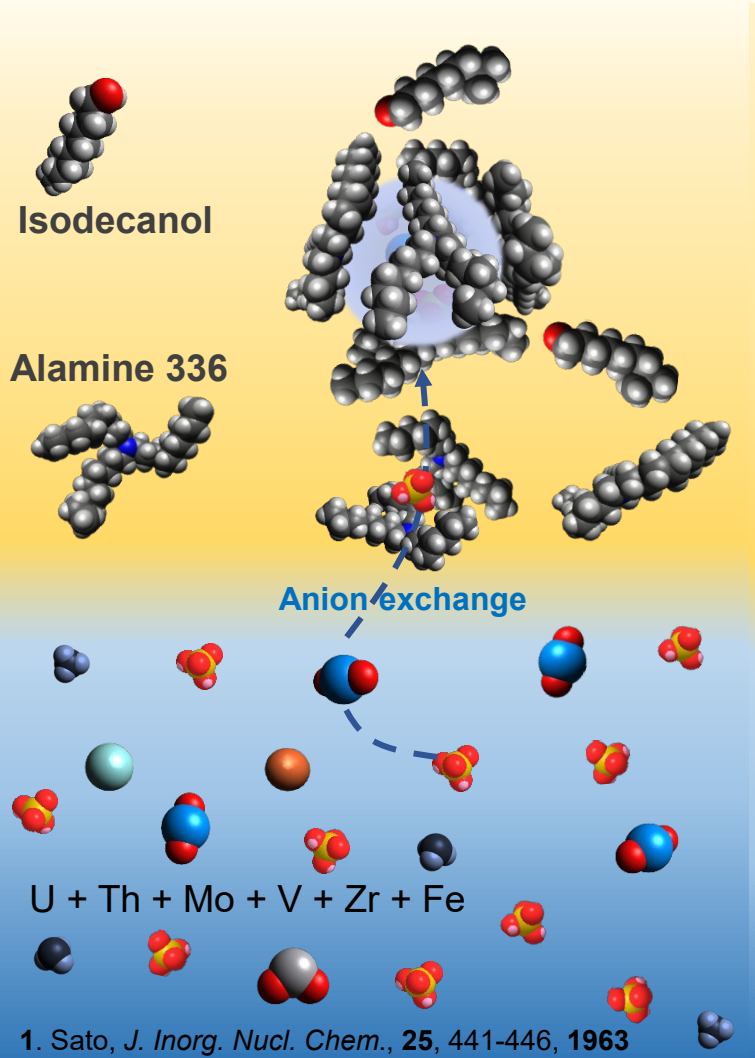
- LLE processes involved
  - ➢ Similar processes are applied in both cases
  - ➢ From nitric, hydrochloric or sulfuric media

*WEEE = Waste from Electrical and Electronic Equipment

LEE for selective separation of actinides and lanthanides

❑ AMEX process

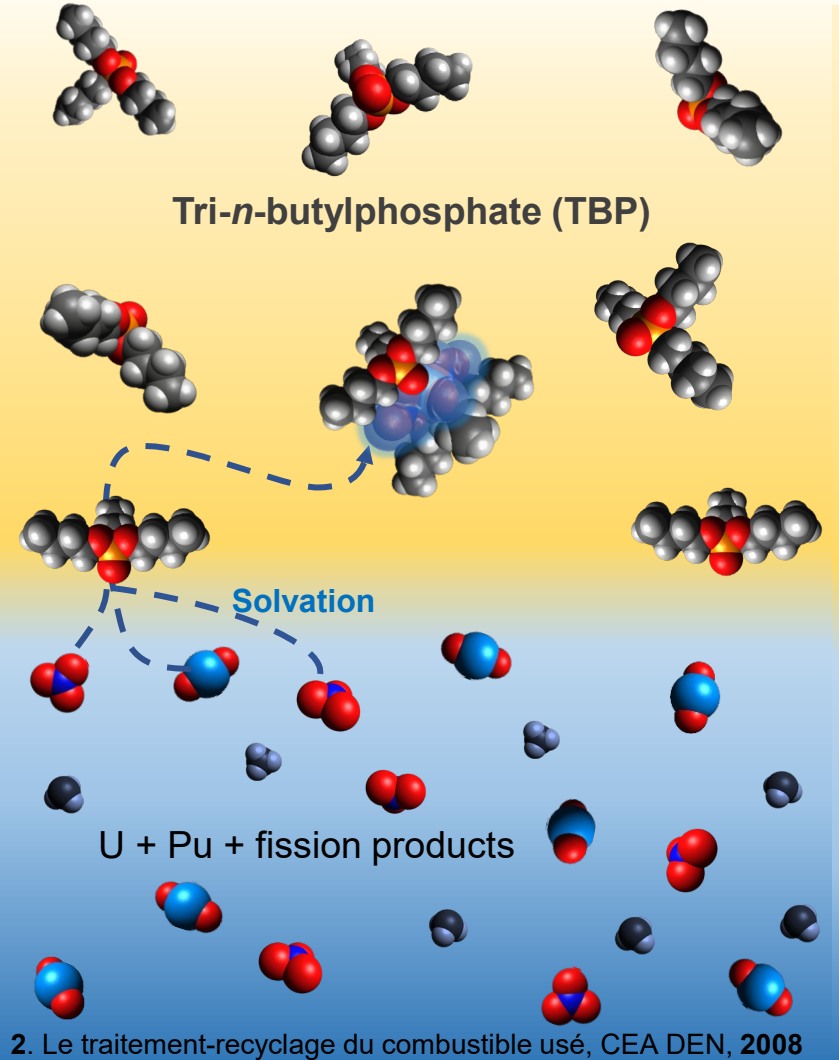
$$\overline{2\,(R_3NH)_2SO_4} + UO_2SO_4 \rightleftharpoons \overline{(R_3NH)_4UO_2(SO_4)_3} \quad (1)$$



1. Sato, *J. Inorg. Nucl. Chem.*, **25**, 441-446, **1963**

❑ PUREX process

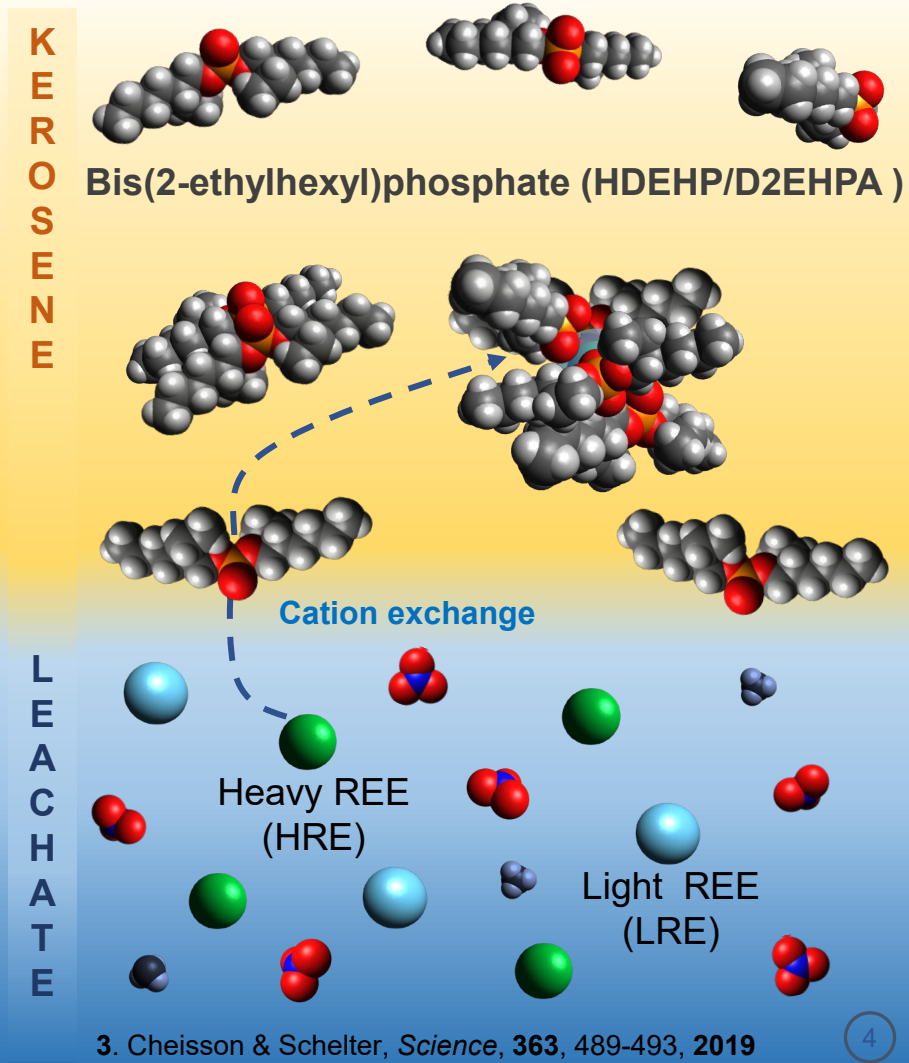
$$\overline{2\,TBP} + UO_2(NO_3)_2 \rightleftharpoons \overline{(TBP)_2UO_2(NO_3)_2} \quad (2)$$



2. Le traitement-recyclage du combustible usé, CEA DEN, **2008**

❑ REEs extraction

$$\overline{3\,(HDEHP)_2} + RE^{3+} \rightleftharpoons \overline{RE(H(DEHP)_2)_3} + 3\,H^+ \quad (3)$$



3. Cheisson & Schelter, *Science*, **363**, 489-493, **2019**

Limitations of LLE Processes Applied at Large Scale

❑ Selectivity of transfer can be improved

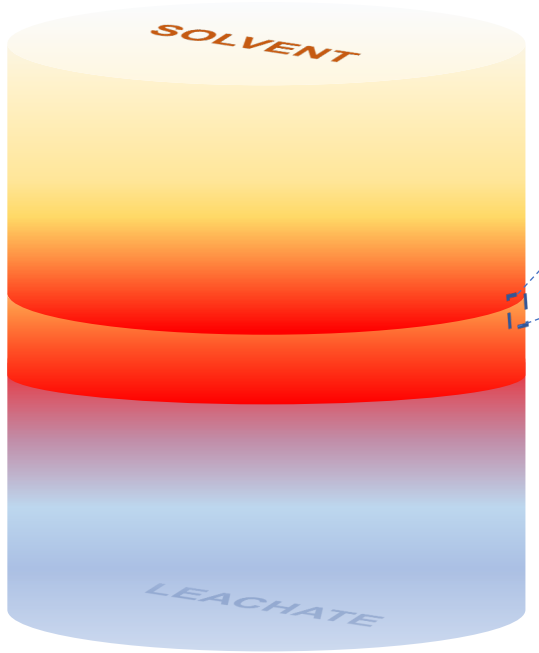
- U vs Fe, V, Mo, Zr (AMEX)[4]
- U vs Fe (URPHOS)[5]
- Ln(III) vs. An(III) (back-end fuel cycle)[6]
- HRE vs LRE[3]
- Intra-lanthanide separation (highly challenging)[3,7]

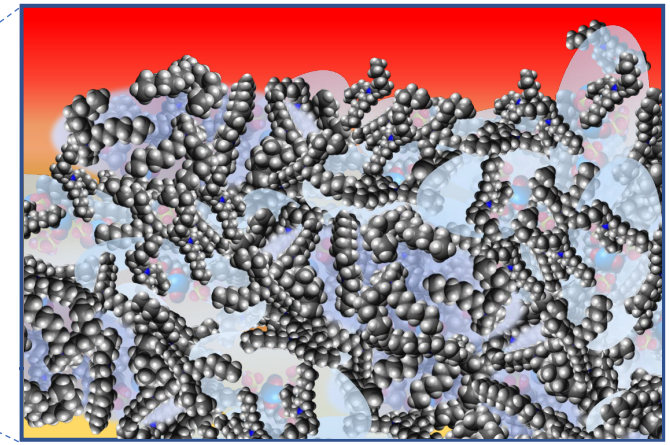
❑ Third phase formation

- Splitting of the organic phase
- AMEX[8]
- REE extraction[9]

= Cumbersome phenomenon that jeopardizes the ELL process

➡ **Must be adressed**



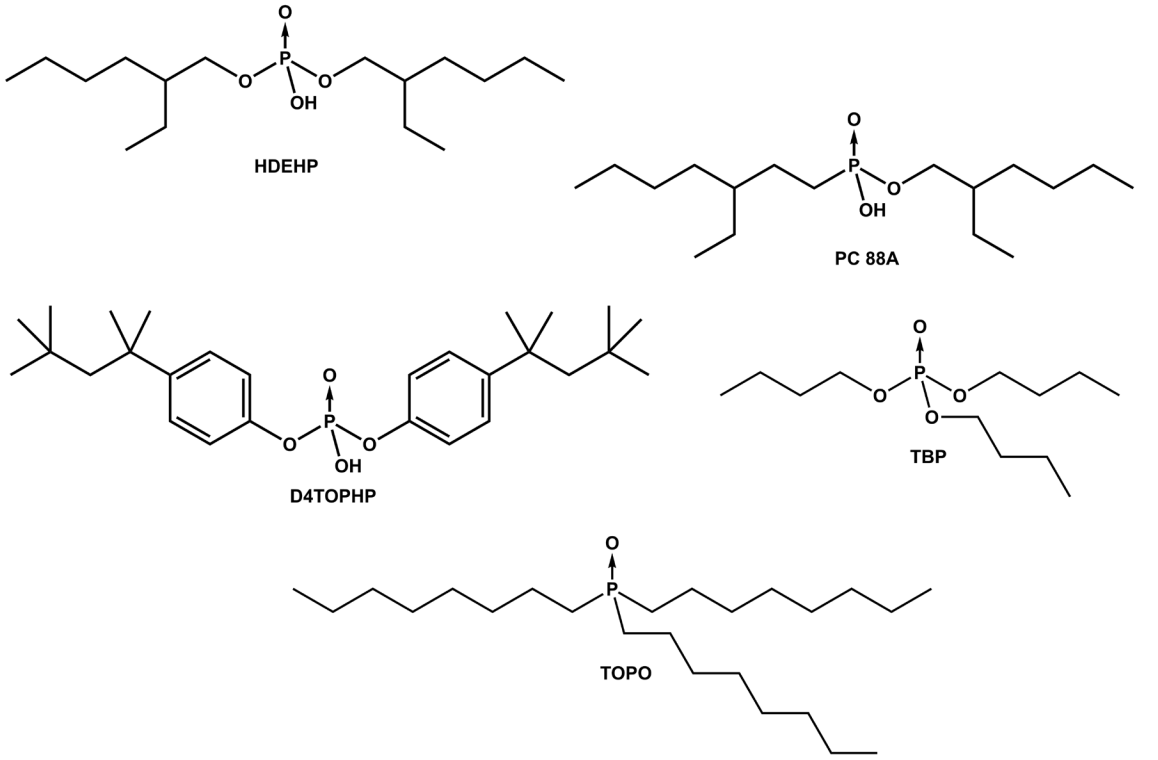


Heavy phase = huge aggregation of ligand and polar material

3. Cheisson & Schelter, *Science*, **363**, 489-493, **2019; 4.** McDonald *et al*., *J. South Afr. Instit.Min.Metall*., **81**, 303-308 **1981**; **5.** Leydier *et al*., Hydrometallurgy, **171**, 262-266, **2017**; **6.** Leoncini et al., Chem. Soc. Rev., **46**, 7229-7273, **2017**; **7.** Stamberga *et al*., *Inorg. Chem*., **59**, 17620-17630, **2020**; **8**. Guérinoni *et al., J. Mol. Liq.,* **403**, 124820, **2024**; **9.** Ellis *et al*., *J. Phys. Chem*. B, **119**, 11910-11927, **2015**.

Limitations of LLE Processes Applied at Large Scale

- **Selectivity of transfer can be improved**
- **Third phase formation**
- **Organophosphorous extractants**
  - "Former" concern
    - Incineration of solvents leads to phosphates accumulation



To be replaced by extractants consisting of C, H, O, N

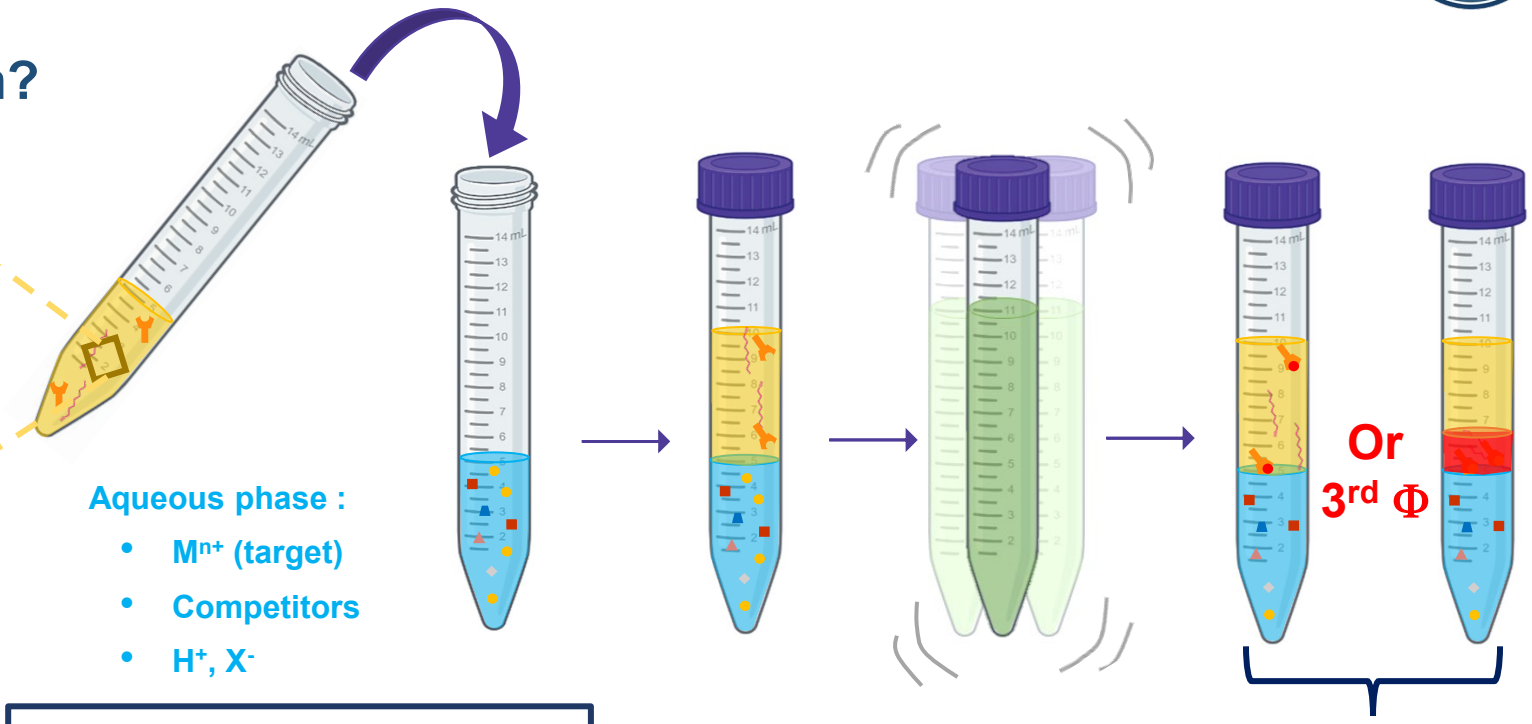
CHON system

Understand and Optimize Processes at the Lab. Scale

❑ Role of constituents? Mechanism?

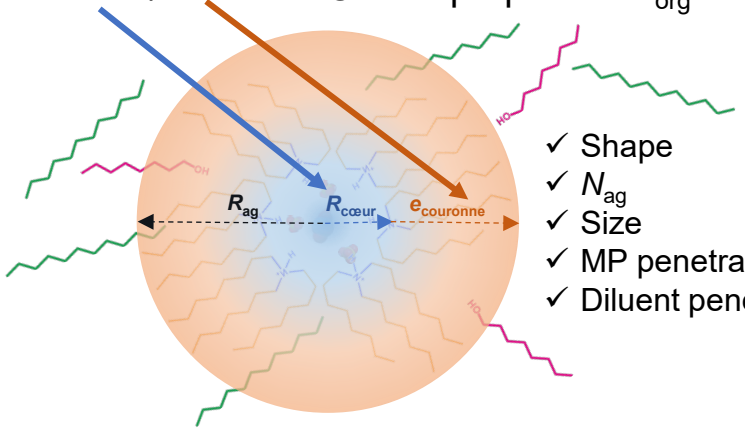
Solvent:

- Extractant: reference or new one
- Diluent: *n*-dodecane
- Phase modifier (MP): 1-octanol



Analysis at equilibrium

- SAXS/SANS => Colloid properties Φ_{org} ?



✓ Shape
✓ N_{ag}
✓ Size
✓ MP penetration
✓ Diluent penetration

- pH-metry/KF => Composition H^+/H_2O Φ_{Org}?
- log *D* = *f*(log [ligand]) => Stœchiometry M:L?
- ln K_{ex} = *f*(1/T) => $\Delta H°$, $\Delta G°$, $\Delta S°$
- Tensiometry => Surface properties + CAC
- ICP => Distribution of M Φ_{Org}/Φ_{aq} ?

$$D_M = \frac{[M]_{org}}{[M]_{aq}} \cdot \frac{V_{org}}{V_{aq}}$$ ⇨ Efficiency

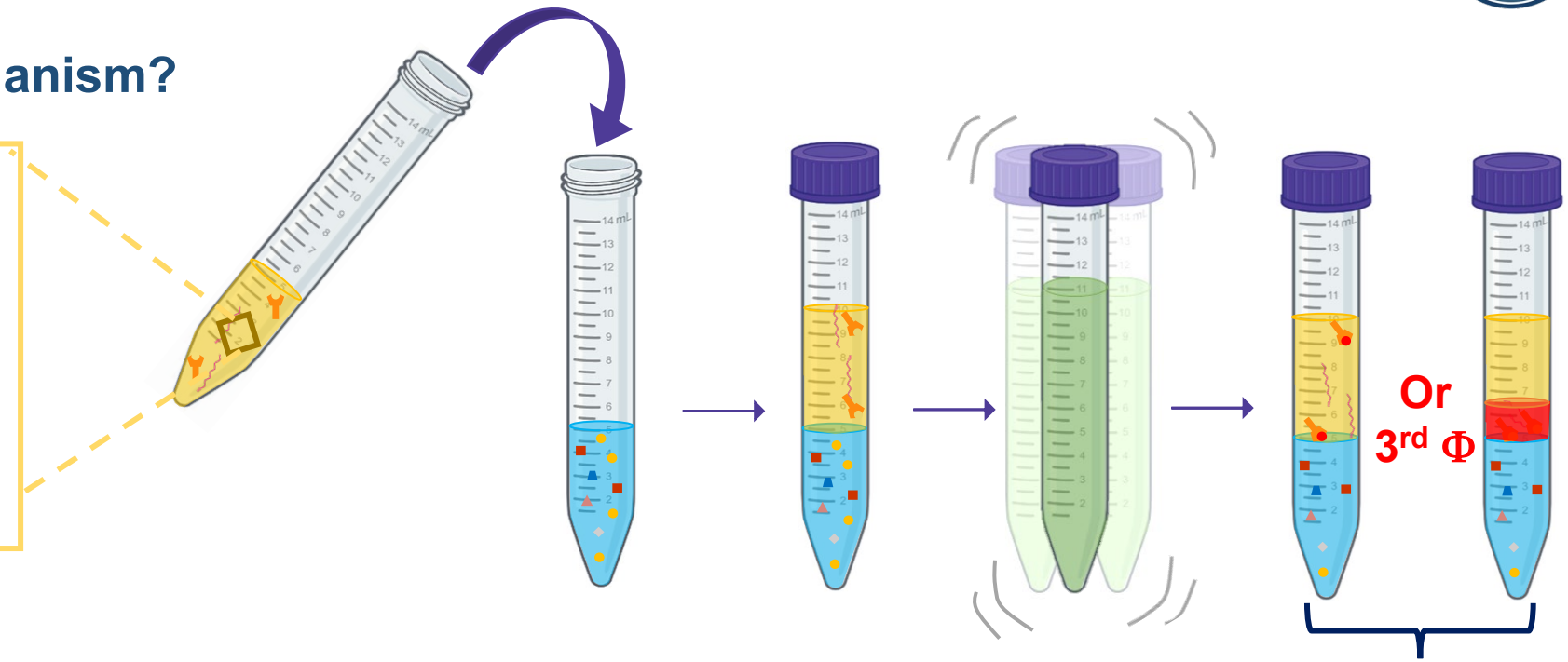
$$SF_{M_1/M_2} = \frac{D_{M_1}}{D_{M_2}}$$ ⇨ Selectivity

Understand and Optimize Processes at the Lab. Scale

❑ Role of constituents? Mechanism?

Solvent:

- Extractant: tailoring the structure
  or
- Diluent: tuning the chains length
  or
- MP: tuning the structure



Analysis at equilibrium

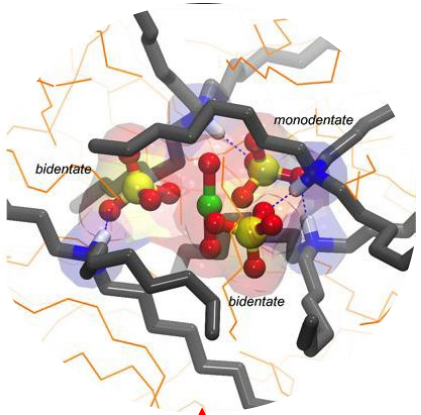
Data collection and processing

RATIONALIZATION:
equations + subtle analysis of
the thermodynamic of the system
⇨ lenaic: extraction = *f*(colloid properties of solvent)

Ienaic Approach: Thermodynamic & Theory[10,11]

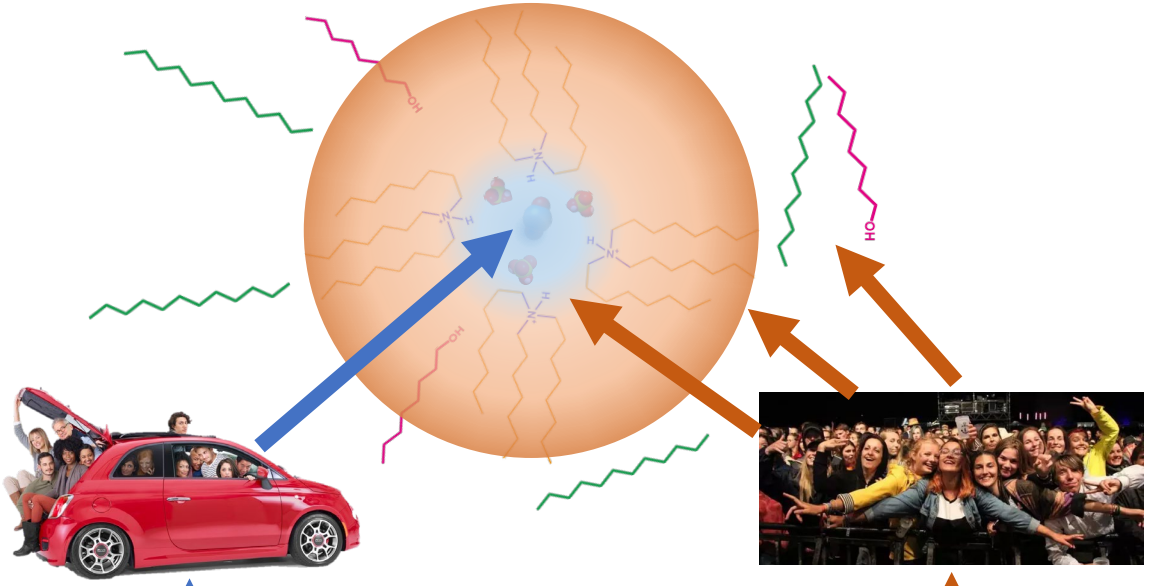
$\Delta G_{transfert} = -k_B T \ln(D_U)$ =

(From Sukhbaatar *et al.*[12])



$\Delta G_{Complexation}$

Complexation of the cation by ligands



+ ΔG_{Drop}

$$\Delta G_{droplet}\left(UO_2^{2+}\right) = i \ln\left(\frac{m^{org}_{SO_4^{2-}}\gamma^{org}_{SO_4^{2-}}}{m^{aq}_{SO_4^{2-}}\gamma^{aq}_{SO_4^{2-}}}\right) + \ln\left(\frac{m^{org}_{UO_2^{2+}}\gamma^{org}_{UO_2^{2+}}}{m^{aq,0}_{UO_2^{2+}}\gamma^{aq}_{UO_2^{2+}}}\right) + i \ln m^{org}_{(R_3NH^+)_2}\gamma^{org}_{(R_3NH^+)_2} + (2i+1)(\Phi^{org} - \Phi^{aq})$$

Containment of polar species in 1 nanogoutte (saturated solution)

+ ΔG_{Chains}

$\Delta G_{Micellisation}$ + $\Delta G_{Courbure}$

$-N_{ag}\ln(CAC)$

Extractants assembled in a reverse micelle

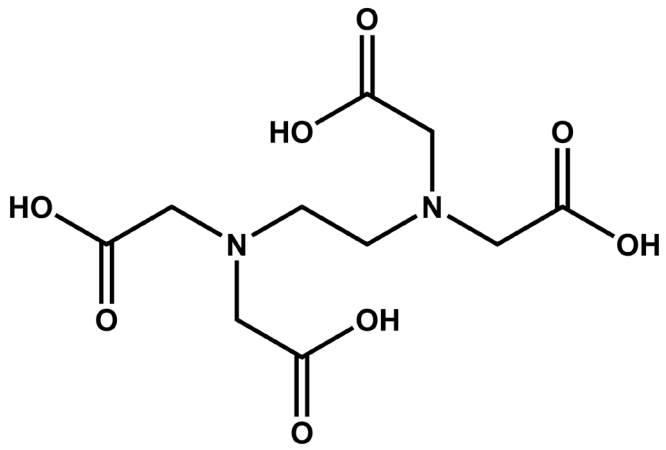
$\frac{K^*}{2} N_{Ag}(P_S - P_e)^2$

Core/Corona Interface biding energy => Film stiffness

10. Dufrêche & Zemb, *Chem. Phys. Lett.*, **622,** 45–49, **2015**; **11**. Rey *et al.*, *Langmuir*, **33**, 13168-13179, **2017**; **12**. Sukhbaatar *et al.*, *Chem. Commun. RSC*, **55**, 7583-7586, **2019**.

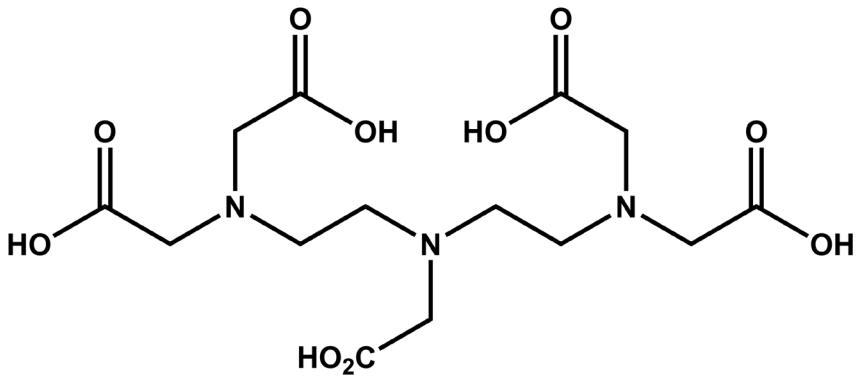
EXAMPLE: Development of Lipophilic AminoPolyCarboxylic Acid Derivatives

What Are AminoPolyCarboxylic Acids (APCAs)?



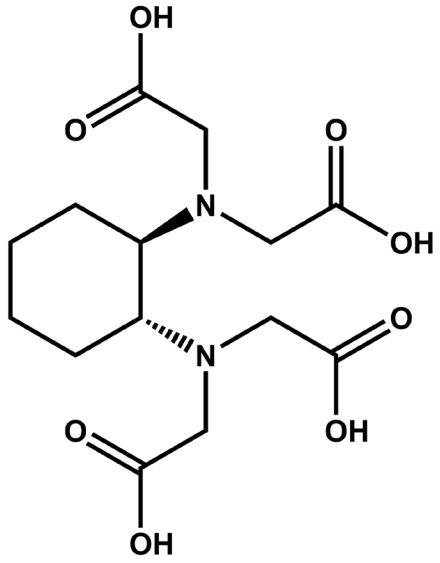
2,2',2'',2'''-(ethane-1,2-diylbis(azanetriyl))tetraacetic acid

EthyleneDiamineTetracetic Acid (EDTA)



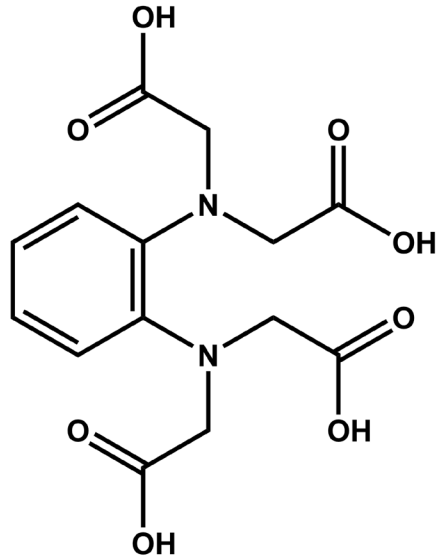
2,2',2'',2'''-((((carboxymethyl)azanediyl)bis(ethane-2,1-diyl))bis(azanetriyl))tetraacetic acid

DiethyleneTriaminePentaacetic Acid (DTPA)



2,2',2'',2'''-(((1*R*,2*R*)-cyclohexane-1,2-diyl)bis(azanetriyl))tetraacetic acid

trans-1,2-CyclohexaneDiamineTetraacetic Acid (CyDTA)



2,2',2'',2'''-(1,2-phenylenebis(azanetriyl))tetraacetic acid

1,2-PhenylDiamineTetraacetic Acid (PDTA)

When/Why/How Developing Lipophilic EDTA Derivatives?

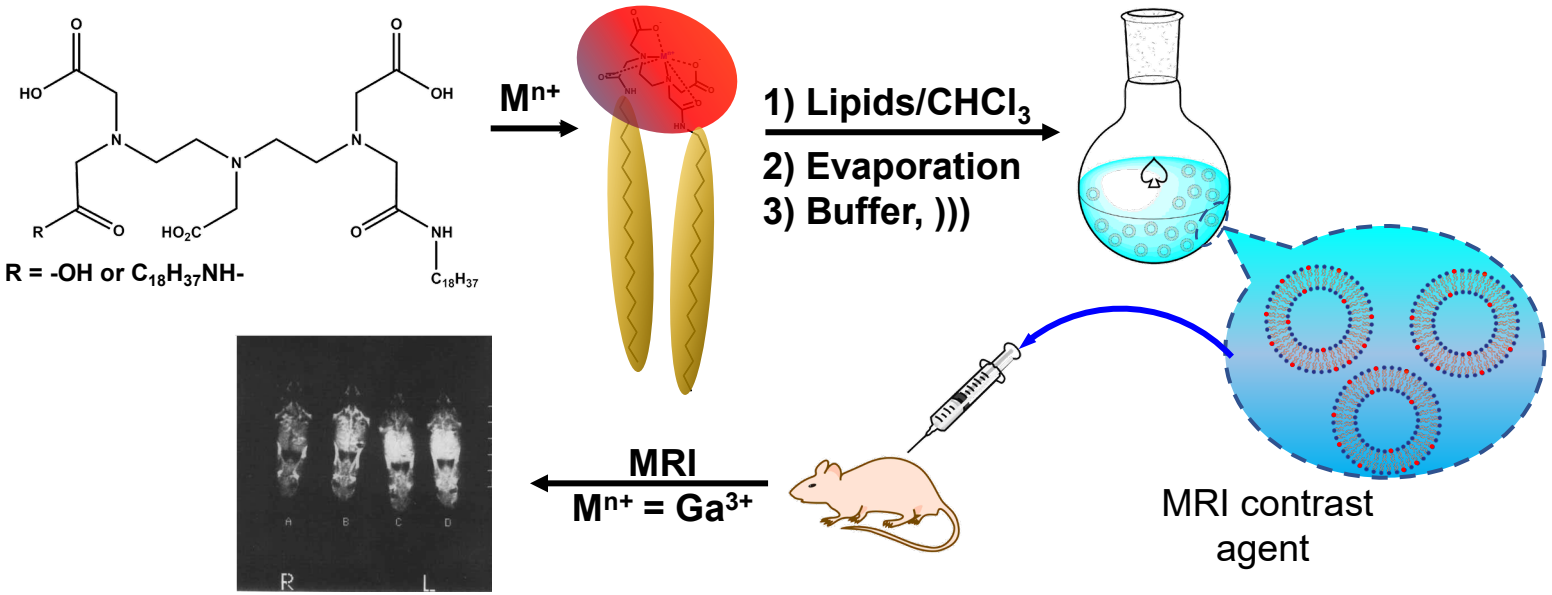
1970 1980 1990 2000 2010 2020 2024

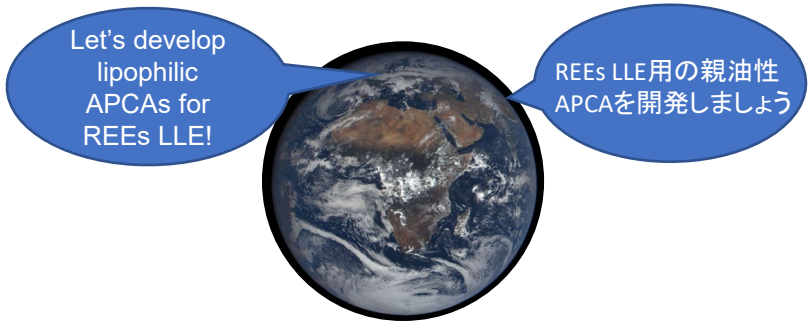
Development of **hydrophobic** EDTA/DTPA derivatives as surfactants or MRI contrast agents[13]

Development of hydrophobic EDTA/DTPA diamide derivatives

Development of hydrophobic *C*-alkylated EDTA/DTPA derivatives

Development of **lipophilic** EDTA/DTPA derivatives for LLE of metal cations





- Technical note ICSM in 2014[14]
- Claimed but not achieved in a Japanese patent in 2015[15]
- Patented in France (ICSM)[16]
- Published by LTSM & co[17]
- ANR (NEODREAM)
- E. Fauvel's Ph. D. (2024-2027)

13. Kabalka *et al*., *Magn. Res. Med*, **19**, 406-415,**1991**; **14.** Mary & Arrachart, Technical note, **2014; 15.** JP2016028021A, **2015**; **16**. FR2210237, **2022**; **17.** Sukhbaatar *et al*., *Hydrometallurgy*, **231**, 106415, **2025**.

When/Why/How Developing Lipophilic EDTA Derivatives?

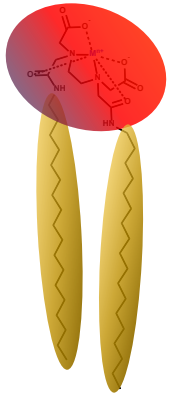
1970 1980 1990 2000 2010 2020 2024

Development of **hydrophobic** EDTA/DTPA derivatives as surfactants or MRI contrast agents[13]

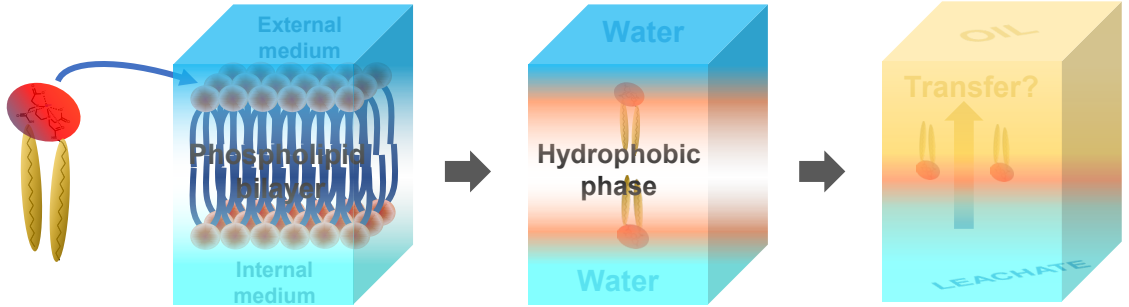
Development of hydrophobic EDTA/DTPA diamide derivatives

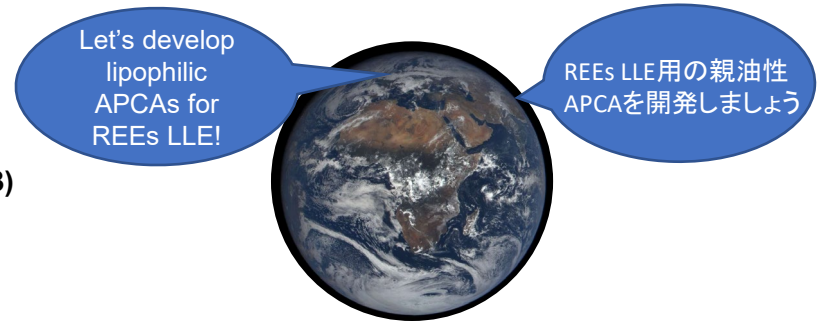
Development of hydrophobic *C*-alkylated EDTA/DTPA derivatives

Development of **lipophilic** EDTA/DTPA derivatives for LLE of metal cations



- **Isolated ligand-REE complex easily incorporated in lipids membrane[13]**
  - Ligand-REE complex is typically more lipophilic than the free ligand
  - Transfer of REE in solvent should be favored





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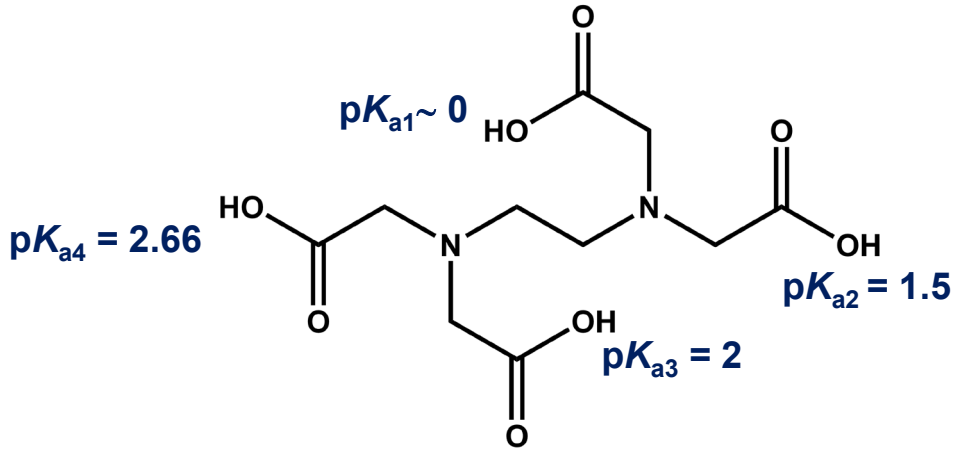
When/Why/How Developing Lipophilic APCAs Derivatives?

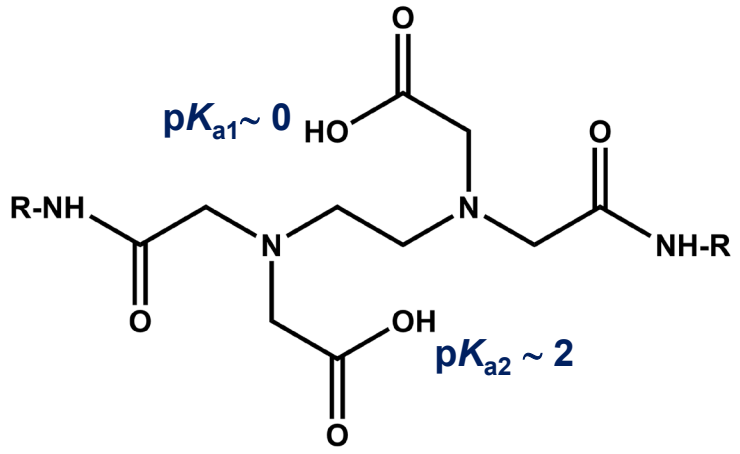
❑ High affinity[15-17] of parent molecules towards lanthanides and actinides

- $LH_4 + M^{n+} \overset{K}{\rightleftharpoons} [LH_{4-n}M] + nH^+$ with $K \sim 10^{15}$-10^{30}
- But poor intra-Ln selectivity[3]
  - ➢ Tuning affinity/selectivity by chemical modification
    - ✓ Modification of carboxylic acid function => affinity lowered by 1000[18]
    - ✓ Modification of the hydrocarbon backbone increases affinity by 10-100[19]

❑ Potential CHON cation exchanger

- Strong first acidity maintained after modification[20]
  - ➢ Advantageous replacement of organophosphorus extractants





With R = *i*Pr or *t*Bu

15. Martell & Smith, *Critical Stability Constants,* **6***,* **1989**; **16.** Cernochova *et al*., *Radiochim. Acta*, **93**, 733-739, **2005**; **17.** Thakur *et al*., *Radiochim. Acta*, **101**, 221-232, **2013; 18**. Keana *et al*., *J. Org. Chem*., **55**, 2868-2871, **1990**; **19**. Smith & Martell, Critical Stability Constants, Vol. 4-6, **1974-1983**; **20.** Wang *et al*., *Polyhedron*, **18**, 109-117, **1999**.

When/Why/How Developing Lipophilic APCAs Derivatives?

❑ Potential applications in the fuel cycle

- Front-end process: extraction of U from sulfuric or phosphoric leachates (E. Fauvel's Ph. D.)
- Back-end process: reversal of the SANEX
  - ➢ Hydroxylated EDTA analogous (HEDTA) used in the SANEX process of the fuel cycle
  - ➢ Amphiphilic derivatives as bypass for actinides recovering in organic medium

❑ Recycling of REEs from WEEEs via LLE (CEFIPRA project 2017-2021)

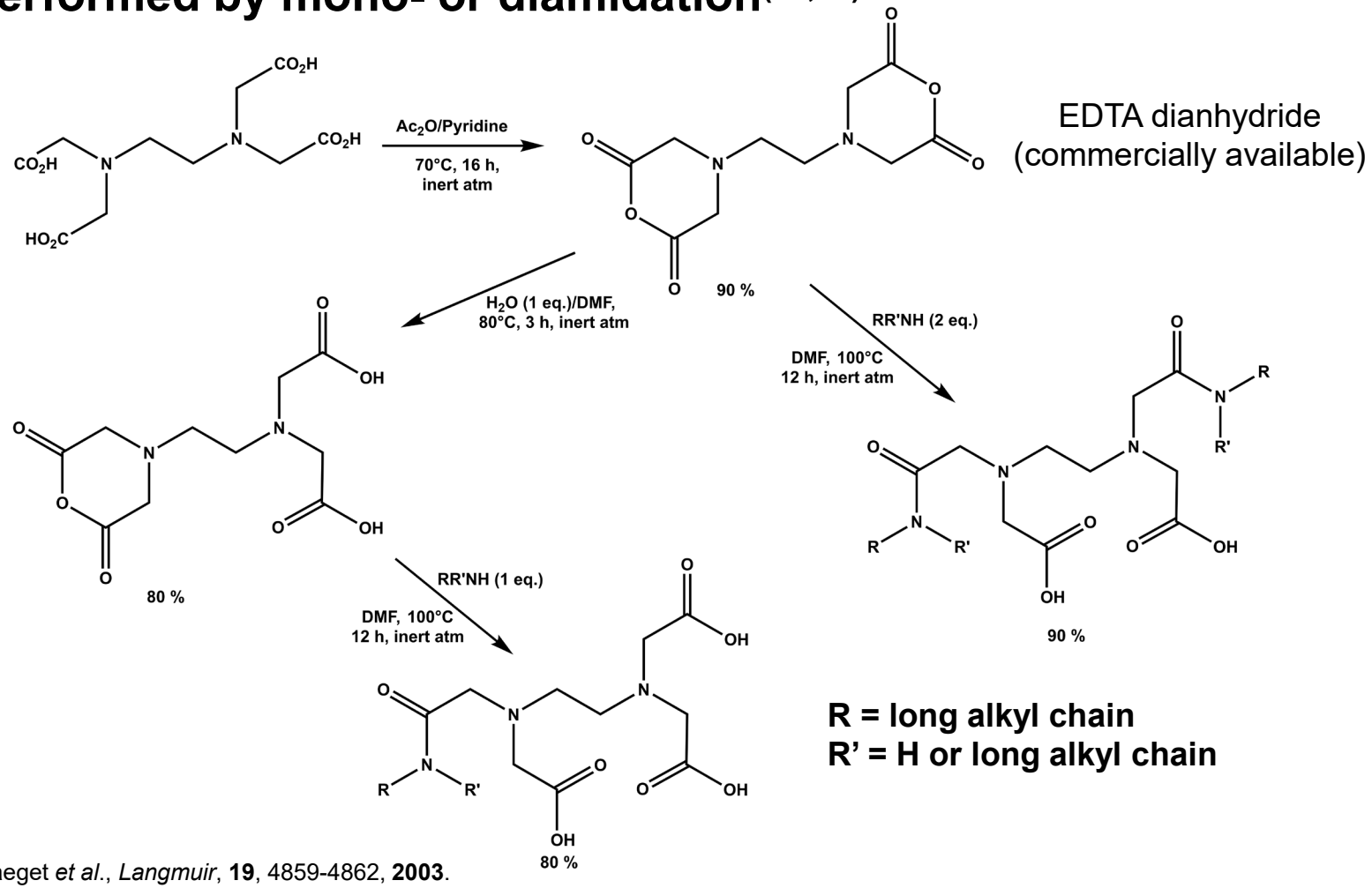
Marcoule Institute of Separation Chemistry

Terra Nova Development

When/Why/How Developing Lipophilic APCAs Derivatives?

- **Hydrophobic modification of APCAs must yield lipophilic derivatives**
  - Solubility ≥ 0.2 M in *n*-dodecane

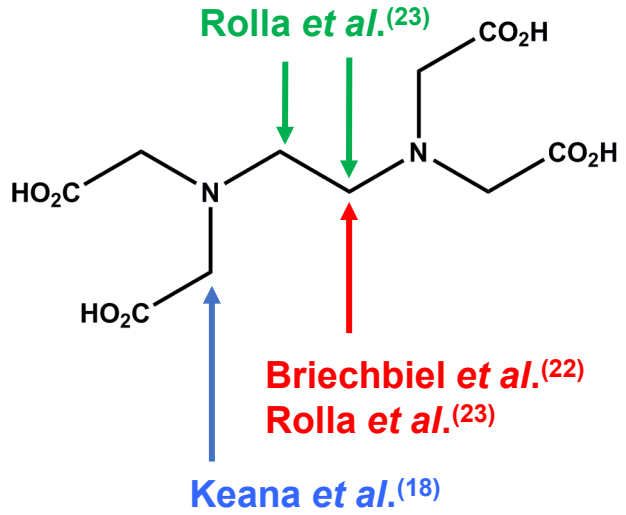
- **Modification may be performed by mono- or diamidation[13,21]**

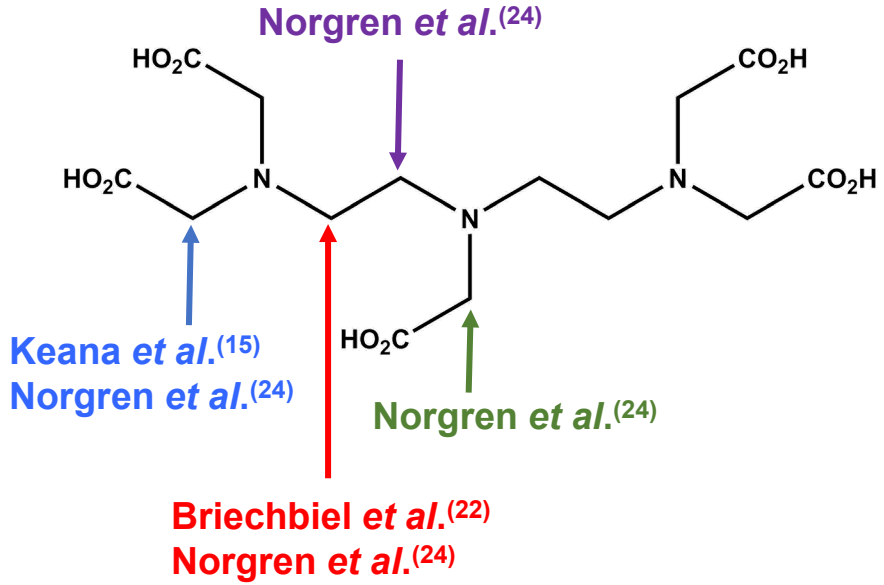


13. Kabalka *et al*., *Magn. Res. Med*, **19**, 406-415,**1991**; **21.** Jaeget *et al*., *Langmuir*, **19**, 4859-4862, **2003**.

When/Why/How Developing Lipophilic APCAs Derivatives?

- **Hydrophobic modification of APCAs must yield lipophilic derivatives**
  - Solubility > 0.2 M in *n*-dodecane
- **Modification may be performed by mono- or diamidation[13,21]**
- **Modification may be performed on hydrocarbon backbone[18,22-24]**

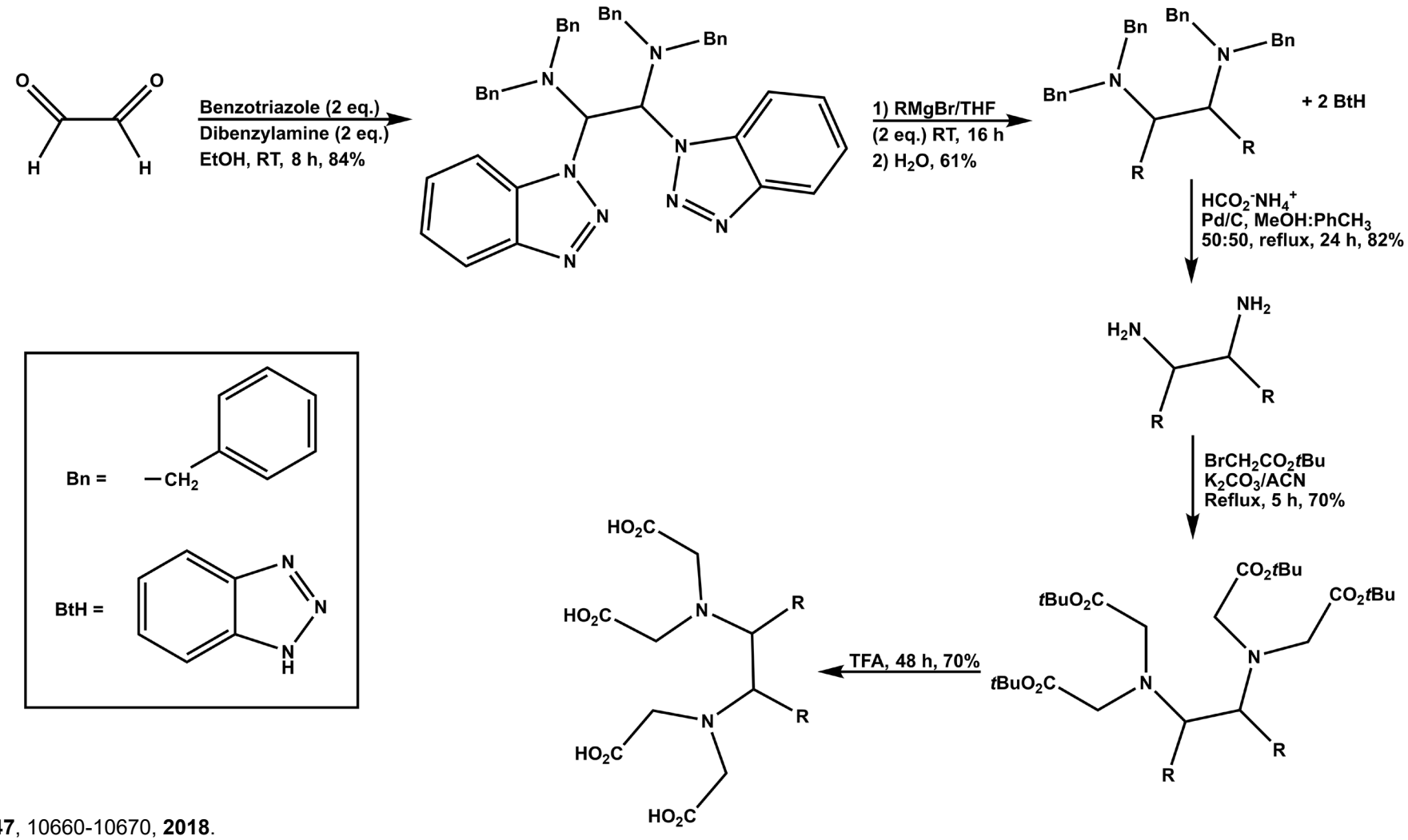




18. Keana *et al.*, *J. Org. Chem.*, **55**, 2868-2871, **1990**; **22.** Brechbiel *et al.*, *Inorg. Chem.*, **25**, 2112-2181, **1986**; **23.** Rolla *et al.*, Dalton Trans., **47**, 10660-10670, **2018**; **24.** Norgren *et al.*, *US Patent*, 8,658,814 B2, **2014**.

When/Why/How Developing Lipophilic APCAs Derivatives?

- **Modification may be performed on hydrocarbon backbone**[18,22-24]
  - Example: synthesis of symetrical di-*C*-alkylated EDTA derivatives[23]



23. Rolla *et al.*, Dalton Trans., **47**, 10660-10670, **2018**.

Synthesis of Lipophilic APCAs Derivatives

❑ Synthesis of APCAs diamide derivatives

- Yield = 60-90%
- Only modification performed with dialkylamines led to derivatives soluble in conventionnal organic solvents
  - ➢ HNR_2 with R = C_8H_{17}-, 2-Ethylhexyl, $C_{10}H_{21}$-, $C_{12}H_{25}$-
- Only one EDTA derivative was found slightly soluble in n-dodecane:octanol mixture
  - ➢ EDTA derivative with R = decyl soluble at 0.015 M in 93:7 n-dodecane:octanol (DOm)
- All CyDTA and PDTA derivatives were found soluble at 0.2 M in pure dodecane
  - **But all compounds were too unstable**
    - ➢ Partial degradation within one week in diluent → **Modification cannot be performed on both carboxylic functions and hydrocarbon backbone**

❑ Synthesis of *C*-alkylated EDTA derivatives

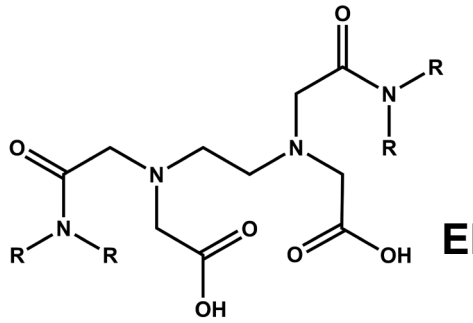
- R = $C_{10}H_{21}$- or $C_{12}H_{25}$-
- 30% overall yield
- Partially soluble in methanol

→ Proof of concept adressed with CyDTA derivatives and EDTA diamide$(C_{10})_4$

Assessment of Extraction Properties: LLE of Ln(III)

❑ **Example: extraction of Nd(III) with ligand diluted in various diluents**[16,17]

- D_M vs pH => cation exchange properties
- From HCl or HNO_3 leachate ($[Nd^{3+}]$ = 0.01 M)
- $[EDTA(C_{10})_4]$ = 0.01 M in various diluents



R = $C_{10}H_{21}$-

$EDTA(C_{10})_4$

- DOm = 93:7 n-dodecane:octanol mixture
- DiPB = 1,3-diisopropylbenzene
- Heptan-2-one
- MiBK = methylisobutyketone
- 11-Undecen-1-ol

Solubility~20 mM

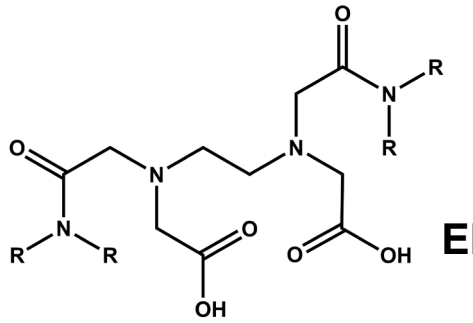
- Chloroform **=> Solubility~100 mM**

16. FR2210237, **2022**; **17.** Sukhbaatar *et al*., *Hydrometallurgy*, **231**, 106415, **2025**

Assessment of Extraction Properties: LLE of Ln(III)

❑ **Example: extraction of Nd(III) with ligand diluted in various diluents**[16,17]

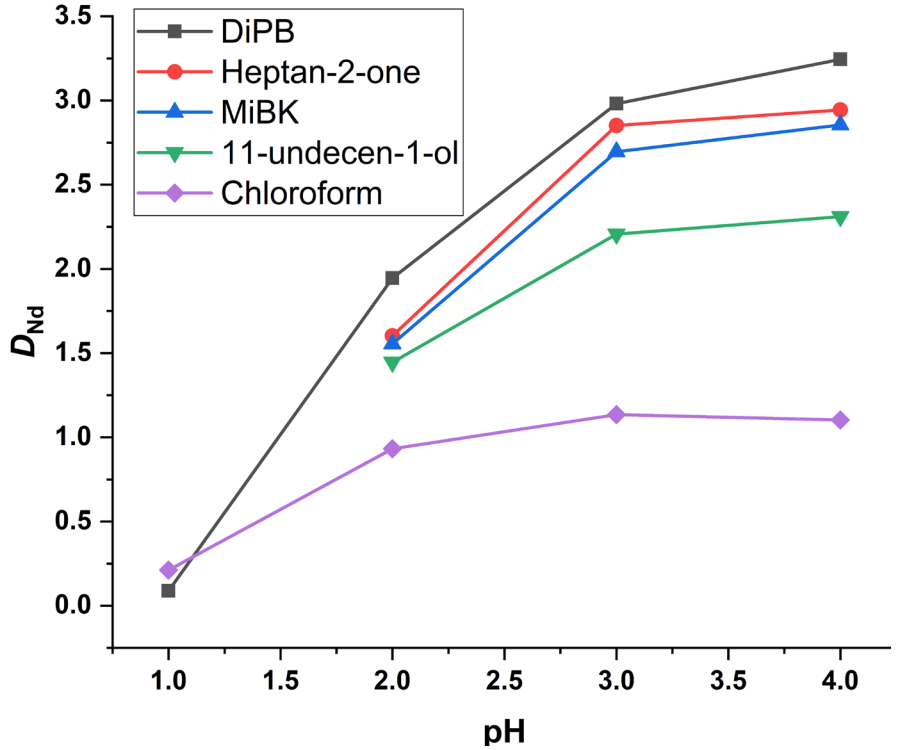
- D_M vs pH => cation exchange properties
- From HCl or HNO_3 leachate ([Nd^{3+}] = 0.01 M)
- [EDTA(C_{10})$_4$] = 0.01 M in various diluents



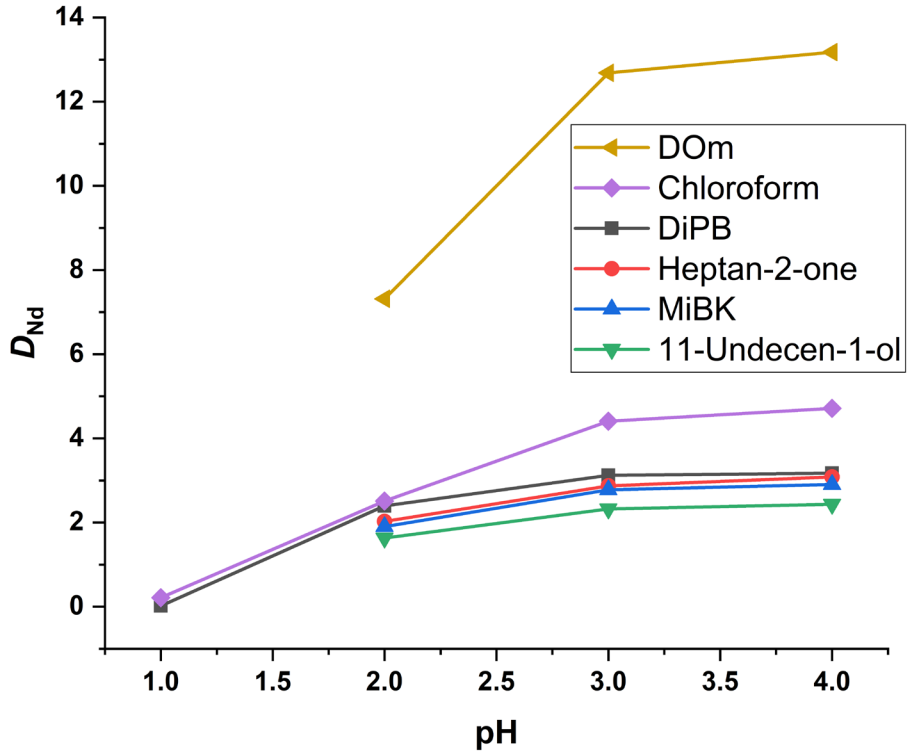
R = $C_{10}H_{21}$-

EDTA(C_{10})$_4$

HCl



HNO_3



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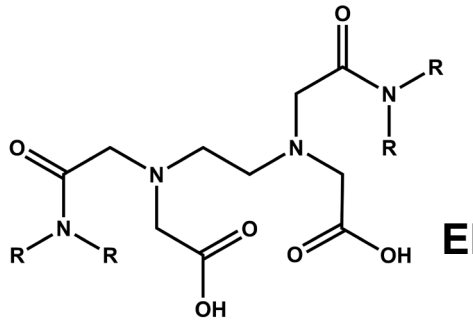

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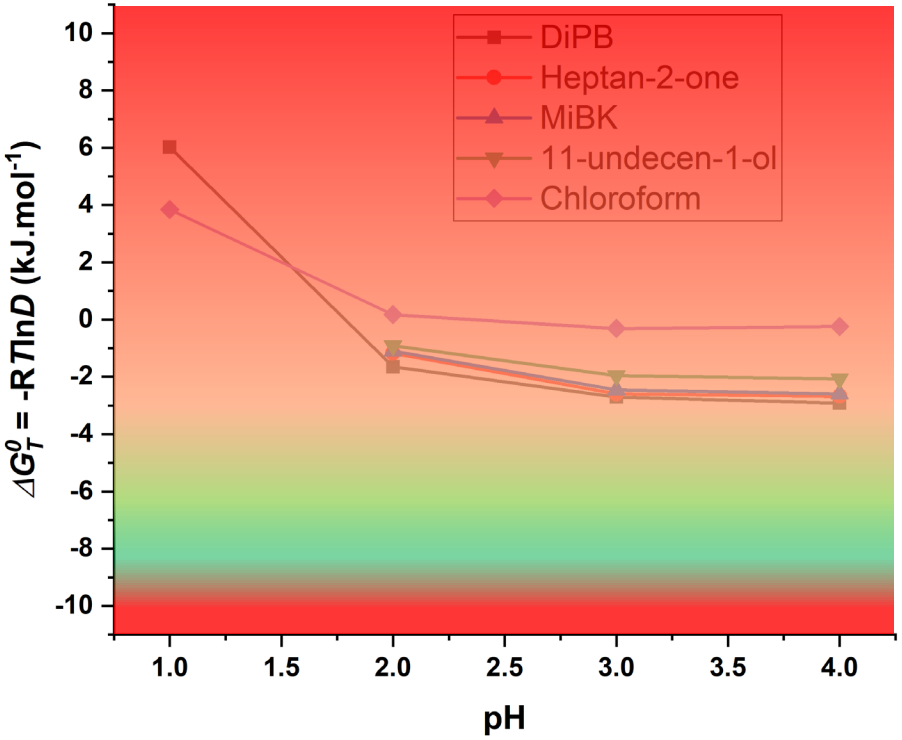
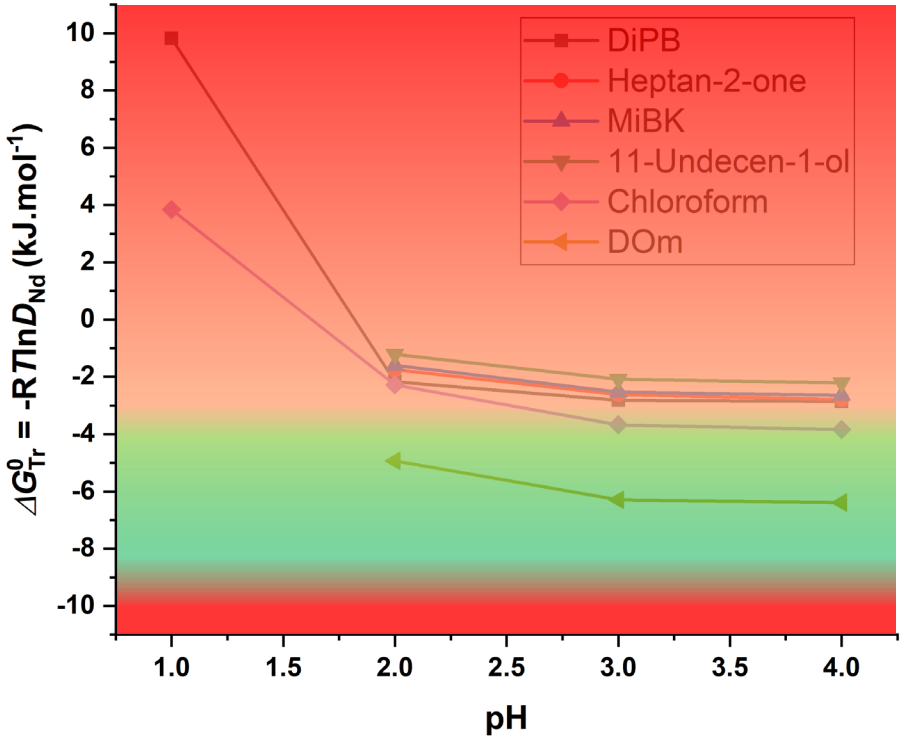


HNO_3



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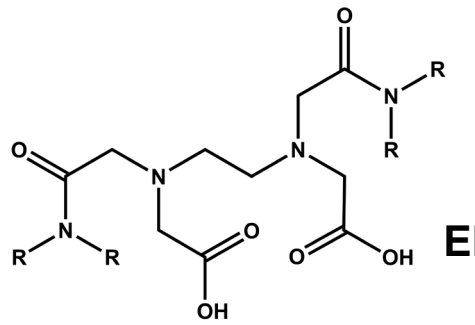

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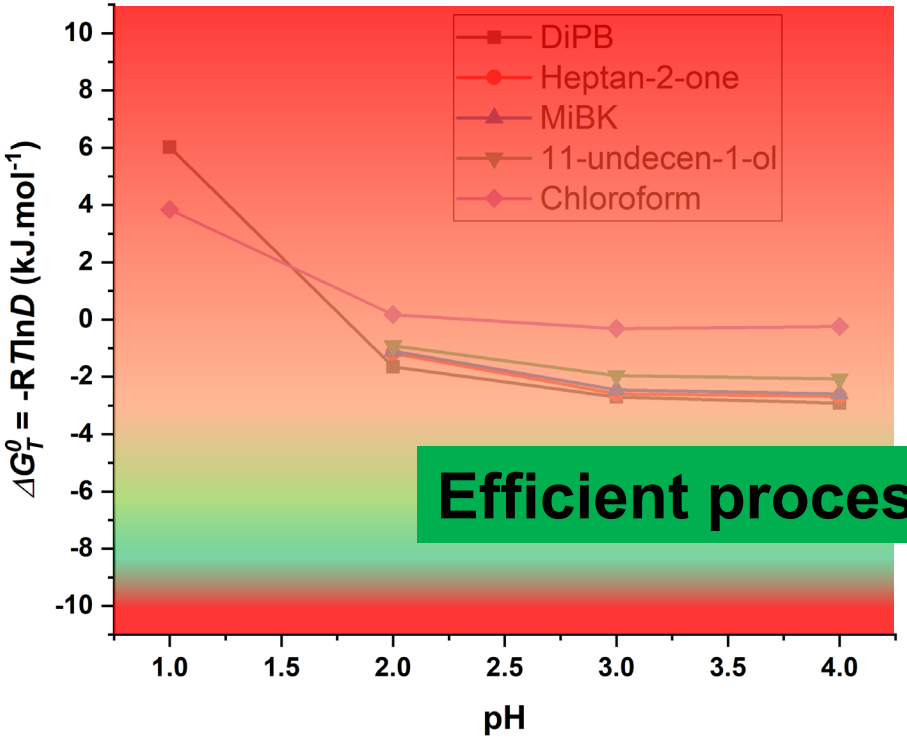
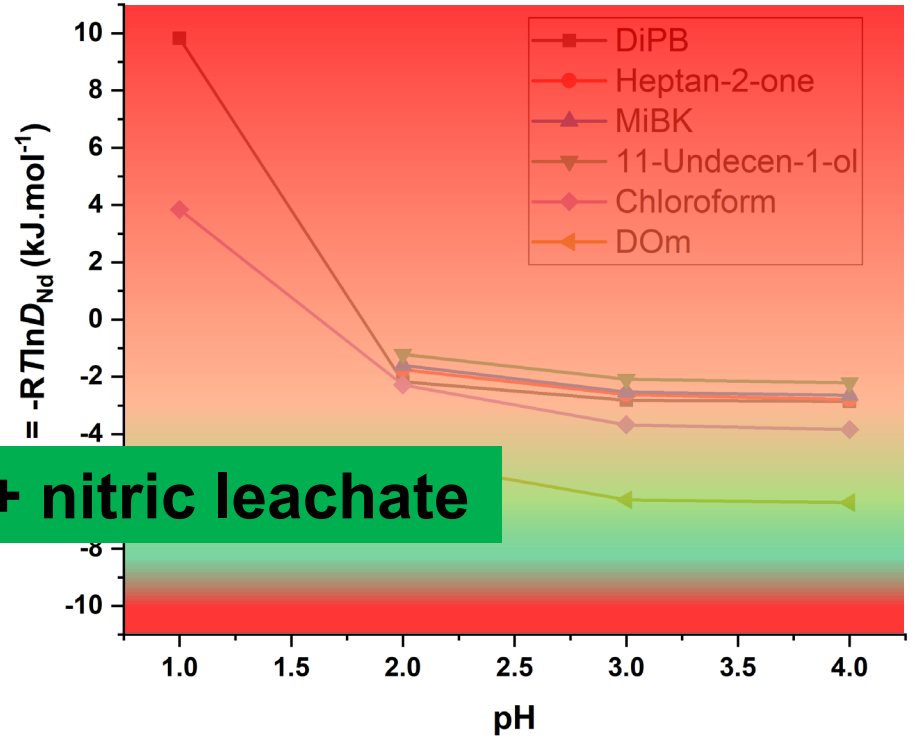
HCl



HNO_3



Efficient process = DOm + nitric leachate

16. FR2210237, **2022**; **17.** Sukhbaatar *et al*., *Hydrometallurgy*, **231**, 106415, **2025**

Assessment of Extraction Properties: LLE of Ln(III)

❑ **Example: extraction of Nd(III) with ligand diluted in various diluents**[16,17]

- ΔG_{Tr} vs polarity of the diluent
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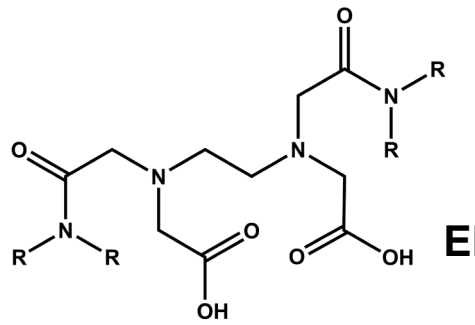
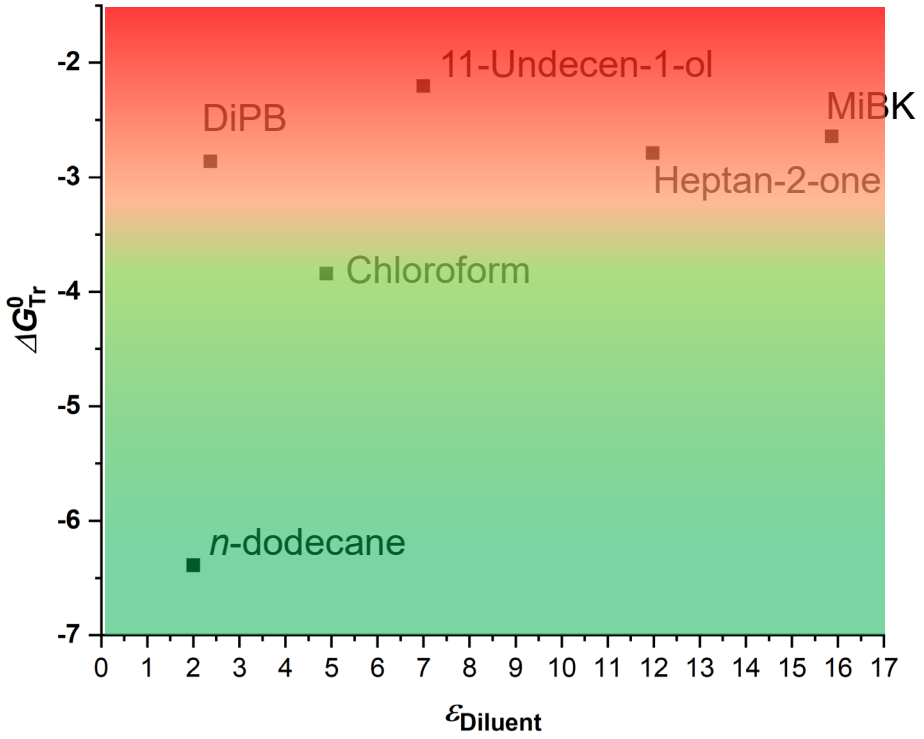
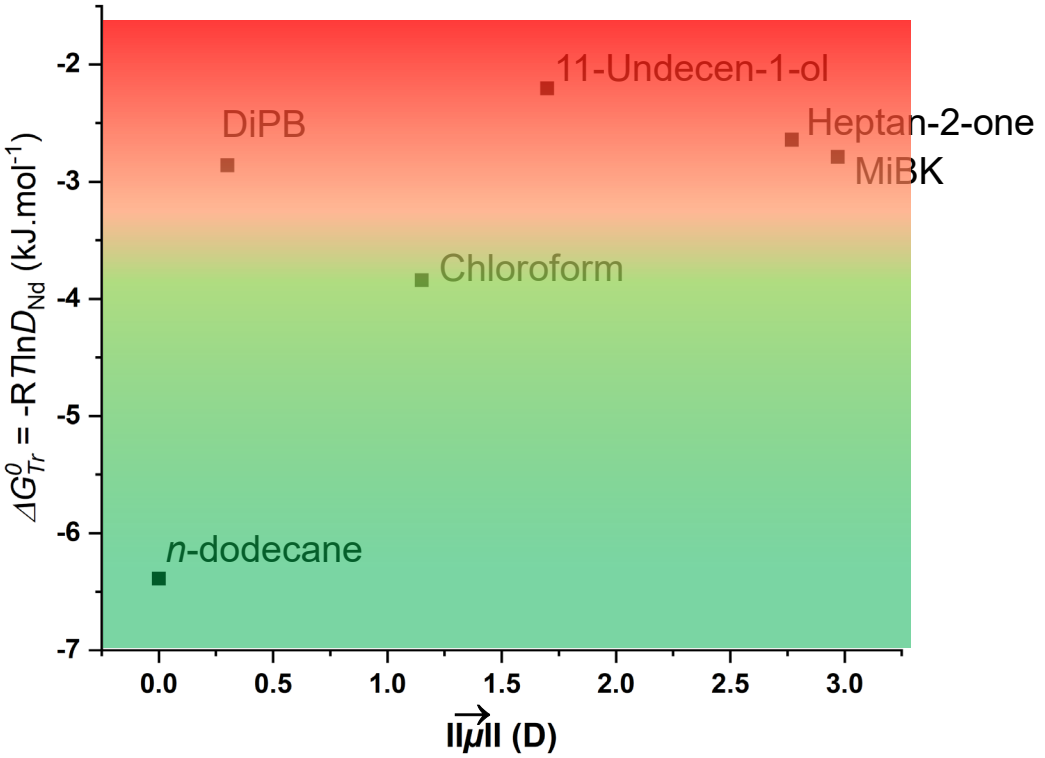


R = $C_{10}H_{21}$-

EDTA(C_{10})$_4$

=> Low polarity => Aggregation ↑ => extraction ↑ ↑





16. FR2210237, **2022**; **17.** Sukhbaatar *et al*., *Hydrometallurgy*, **231**, 106415, **2025**

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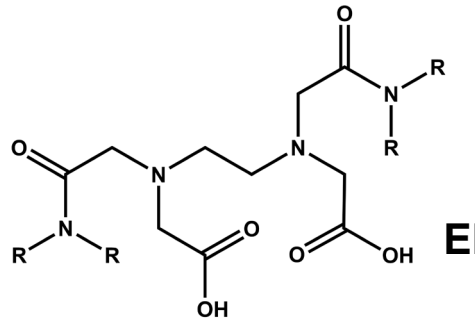
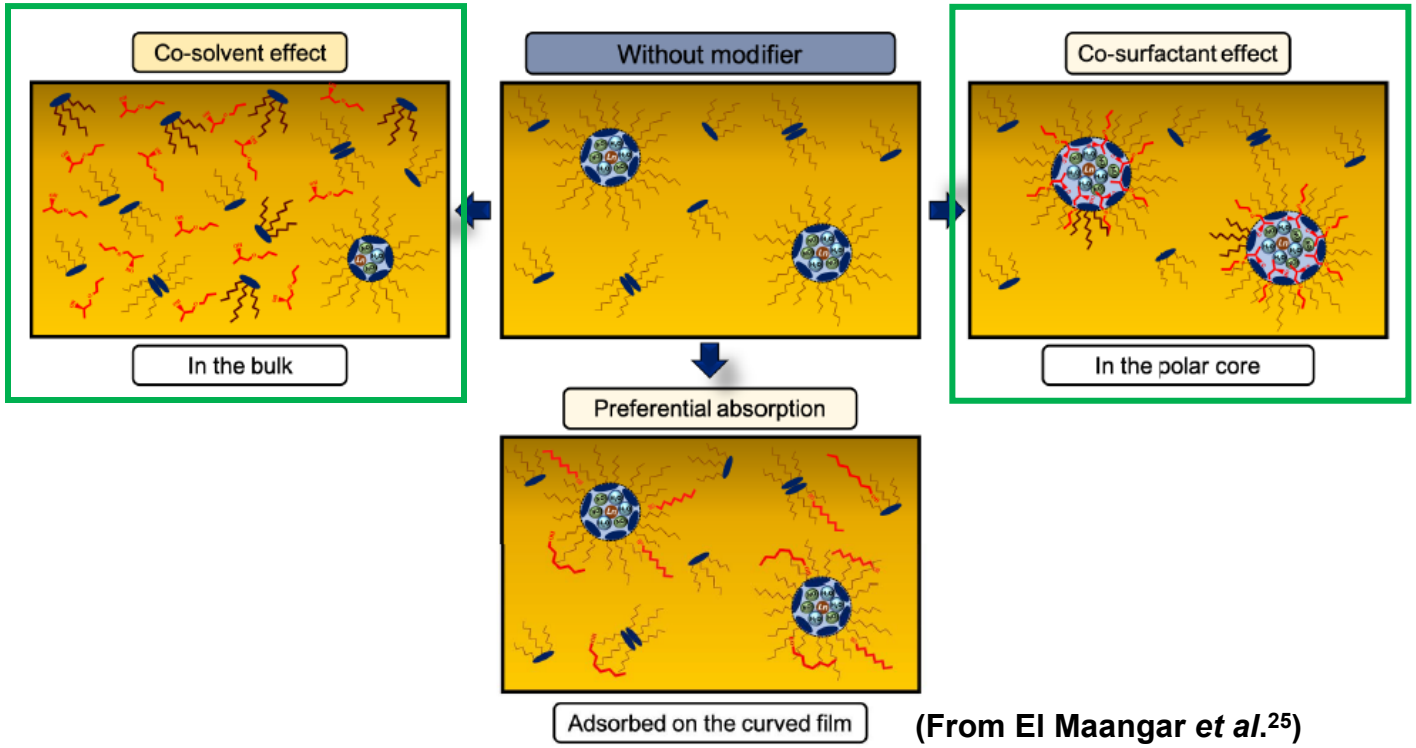


R = $C_{10}H_{21}$-

EDTA(C_{10})$_4$

=> Role of the phase modifier (PM)

PM increases the solubility in *n*-dodecane



PM increases the stability of aggregates in *n*-dodecane

(From El Maangar *et al.*[25])

25. El Maangar *et al.*, *CRAS*, **25**, 341-360, **2022**

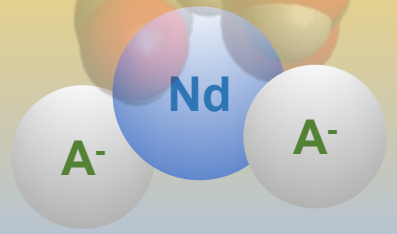
Assessment of Extraction Properties: LLE of Ln(III)

Diluent

$$Nd^{3+}_{(aq)} + a\ A^{-}_{(aq)} + n\ H_2EDTA(C_{10})_4 \overset{K_{eq}}{\rightleftharpoons} \overline{NdA_a(H_xEDTA(C_{10})_4)_n} + (3 - a)\ H^{+}_{(aq)}$$

- Log*D* vs [EDTA(C_{10})$_4$] => *n* = 1 in $CHCl_3$
- $\overline{HLNdA_2}$ is predominant
- Extraction is entropy-driven in DiPB (aromatic) and enthalpy-driven in DOm (aliphatic)
- $\Delta G° = -RT\ln K_{eq} \sim -24$ kJ.mol^{-1} is not affected by media

$$K_{eq} = \frac{D_{Nd} \cdot \alpha_{Nd^{3+}} \cdot {\gamma_{H^+}}^3 \cdot [H^+]^3_{eq}}{\gamma_{Nd^{3+}} \cdot [\overline{H_2EDTA(C_{10})_4}]^n_{eq}} \cdot (\gamma_{H^+} \cdot \gamma_{A^-})^{-a} \cdot [H^+]^{-a}_{eq} \cdot [A^-]^{-a}_{eq}$$



LRE

Nd

$SF_{Nd/Pr} \sim 2.2 \Rightarrow \Delta\Delta G_{Tr}° \sim 2$ kJ.mol^{-1} in DiPB

$\Delta\Delta G°_{Complex} \sim 6.3$ kJ.mol$^{-1(3)}$

Pr

LRE

A-

A-

$SF_{Nd/Dy} \sim 1.4$

$\Rightarrow \Delta\Delta G_{Tr}° \sim 0.84$ kJ.mol^{-1} in DiPB

Dy

HRE

HCl or HNO_3 leachate

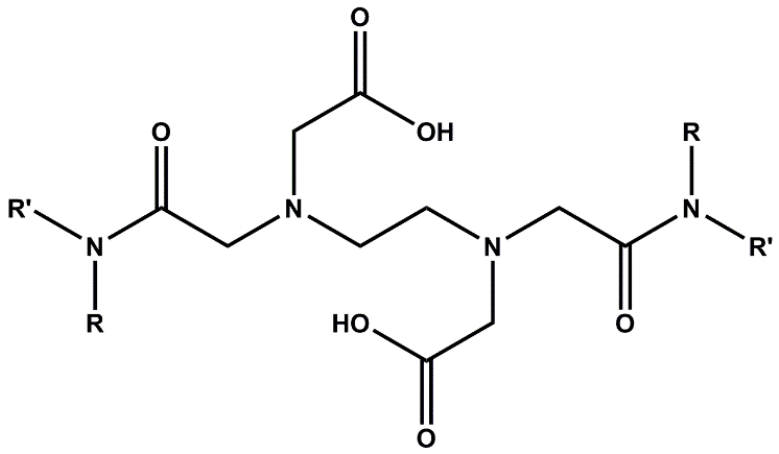
CONCLUSION & OUTLOOK

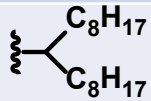
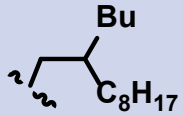
❑ Promising and interesting properties that must be improved

- Solubility in *n*-dodecane must be adjusted to that expected (0.2 M)
- Selectivity intra-Ln must be improved

❑ Molecular tailoring

- Development of new lipophilic APCAs derivatives = first phase of E. Fauvel's Ph. D.
  - ➢ Enhanced lipophilicity provided by branched alkyl chain
  - ➢ Systemic study with various topologies tuned at same carbon number



R	R'	Topology
-*n*-$C_{10}H_{21}$	-*n*-$C_{10}H_{21}$	Symetrical linear
	-*n*-Pr	Disymmetrical branched
	-*n*-Hex	Disymmetrical branched
Neodecyl	Neodecyl	Symetrical branched
2-Ethyloctyl	2-Ethyloctyl	Symetrical branched

-$C_{40}H_{84}$

Acknowledgements

LTSM:

Ienaic experts:

T. Zemb (LTSM)
J.-F. Dufrêche

Partners & fundings:

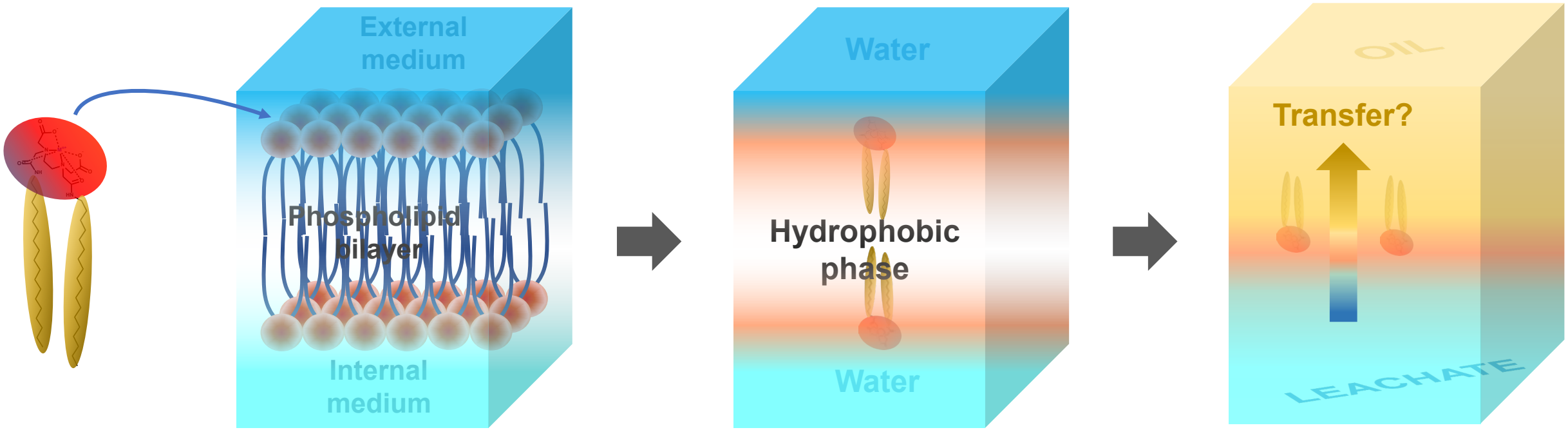
The PROMÉTHÉE GDR

Administrations:

Appendix

When/Why/How Developing Lipophilic APCAs Derivatives?

- **Isolated ligand-REE complex easily incorporated in lipids membrane[13]**
  - Ligand-REE complex is typically more lipophilic than the free ligand
  - Transfer of REE in solvent should be favored
  - Availability of easy handled standards => extraction could be monitored by FX?

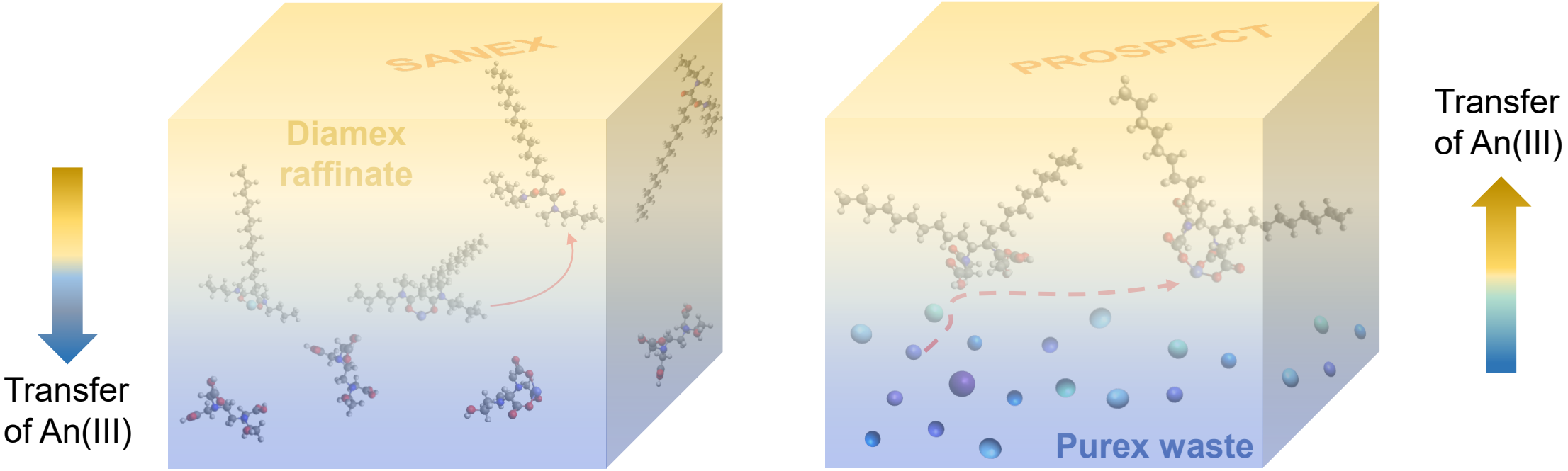


13. Kabalka *et al*., *Magn. Res. Med*, **19**, 406-415,**1991**;

When/Why/How Developing Lipophilic APCAs Derivatives?

❑ Potential applications in the fuel cycle

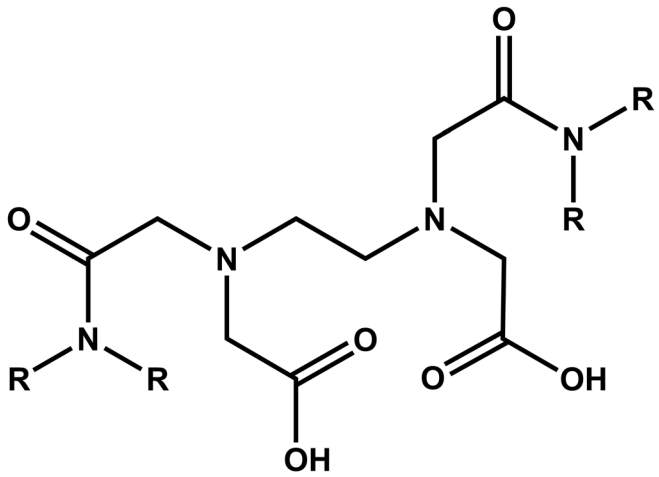
- Front-end process: extraction of U from sulfuric or phosphoric leachates
- Back-end process: reversal of the SANEX
  - ➢ Hydroxylated EDTA analogous (HEDTA) used in the SANEX process of the fuel cycle
  - ➢ Amphiphilic derivatives as bypass for actinides recovering in organic medium



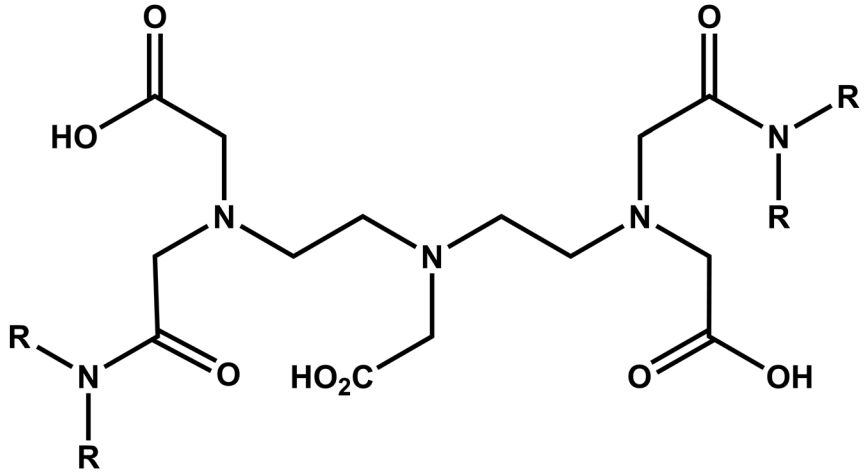
Synthesis of Lipophilic APCAs Derivatives

❑ Synthesis of EDTA and DTPA diamide derivatives

- Only modification performed with dialkylamines led to derivatives soluble in conventional organic solvents

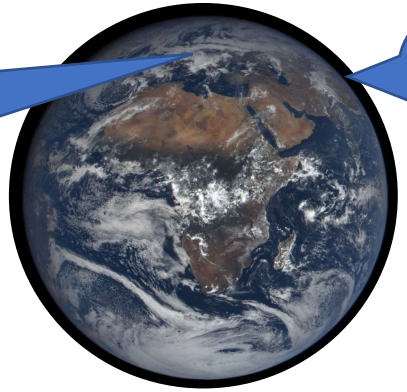


EDTA diamide derivatives



DTPA diamide derivatives

Low chemical stability of the diamide derivatives



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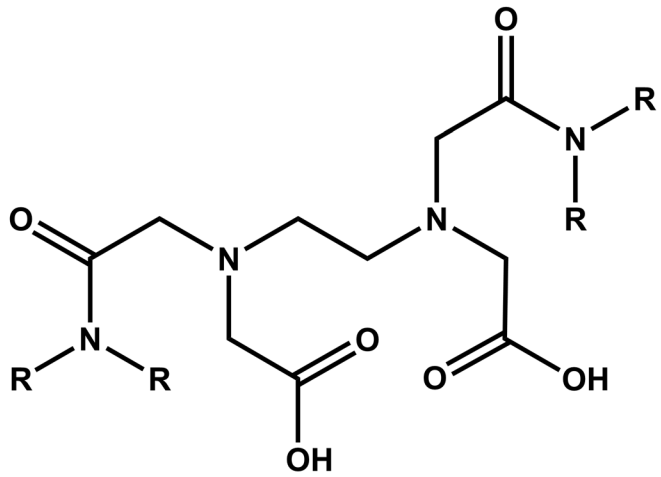
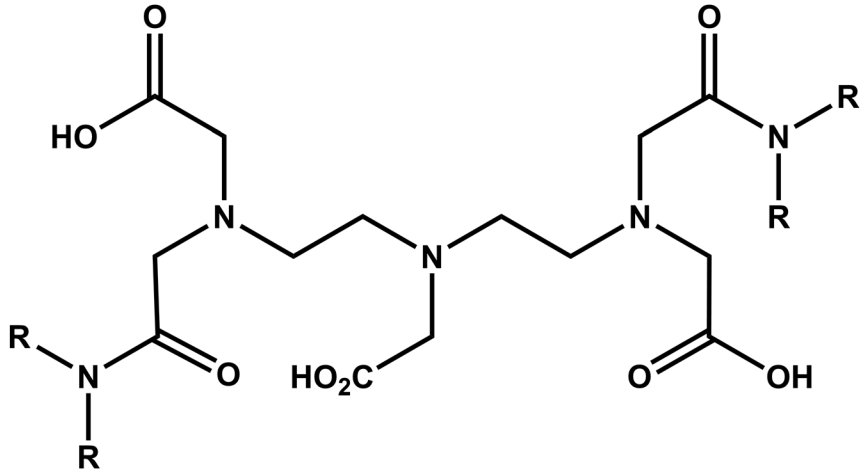


EDTA diamide derivatives



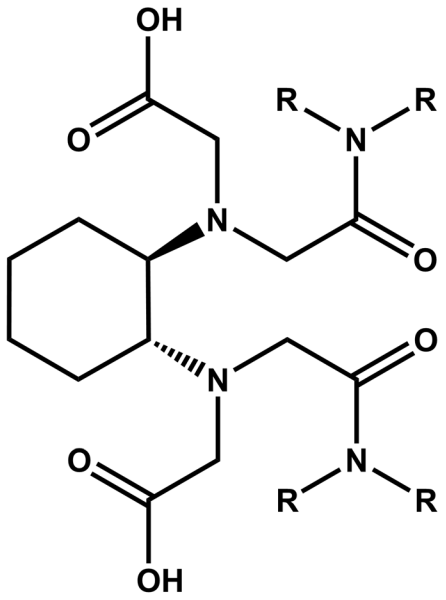
DTPA diamide derivatives

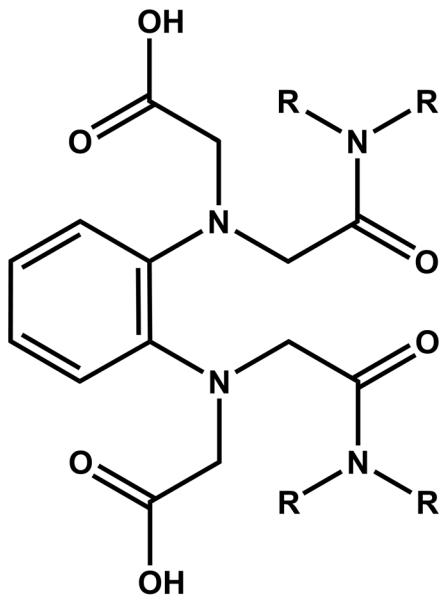
- R = C_8H_{17}-, 2-Ethylhexyl, $C_{10}H_{21}$-, $C_{12}H_{25}$-
- Yield = 70-90%
- Only one compound was found slightly soluble in n-dodecane:octanol mixture
  - ➢ EDTA derivative with R = decyl soluble at 0.015 M in 93:7 n-dodecane:octanol (DOm)

Synthesis of Lipophilic APCAs Derivatives

❑ Synthesis of CyDTA and PDTA diamide derivatives

- Only modification performed with dialkylamines led to derivatives soluble in conventional organic solvents





- R = C_8H_{17}-, 2-Ethylhexyl, $C_{10}H_{21}$-, $C_{12}H_{25}$-
- Yield = 60-70%

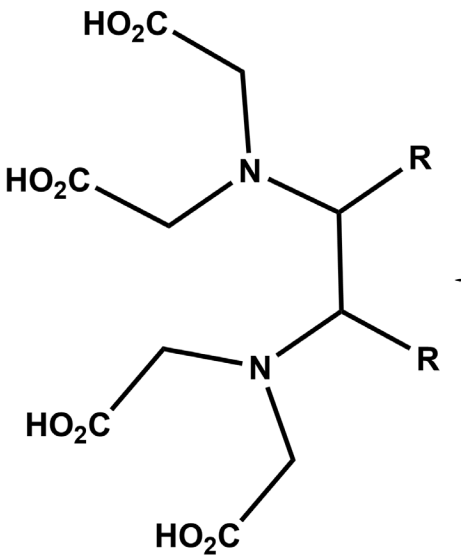
- All compounds were found soluble at 0.2 M in pure dodecane

- **But all compounds were too unstable**
  - ➢ Partial degradation within one week in diluent

Modification cannot be performed on both carboxylic functions and hydrocarbon backbone

Synthesis of Lipophilic APCAs Derivatives

❑ Synthesis of *C*-alkylated EDTA derivatives



- R = $C_{10}H_{21}$- or $C_{12}H_{25}$-
- 30% overall yield
- Partially soluble in methanol
- Attempts for further modification of the carboxylic functions failed
- Expected lipophilicity should be reached after modification of the other methylenes

➡ Proof of concept adressed with CyDTA derivatives and EDTA diamide$(C_{10})_4$