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Actinides

1,10-Phenanthroline and Non-Symmetrical 1,3,5-Triazine Dipicolinamide-Based Ligands For Group Actinide Extraction

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Abstract: The synthesis and evaluation of new extractants for spent nuclear fuel reprocessing are described. New bitopic ligands constituted of phenanthroline and 1,3,5-triazine cores functionalized by picolinamide groups were designed. Synthetic routes were investigated and optimized to obtain twelve new polyaza-heterocyclic ligands. In particular, an efficient and versatile methodology was developed to access non-symmetric 2-substituted-4,6-di(6-picolin-2-yl)-1,3,5-triazines from the 1,3,5-triazapentadiene precursor in the presence of anhydride reagents. Extraction studies showed the ability of both ligand series to extract and separate actinides selectively at different oxidation states (U^{VI}, $Np^{V,VI}$, Am^{III}, Cm^{III}, and Pu^{IV}) from an acidic solution (3 M HNO_3). Phenanthroline-based ligands show the most promising efficiency for use in the group actinide extraction (GANEX) process due to a higher number of donor nitrogen atoms and a suitable pre-organization of the dipicolinamide-1,10-phenanthroline architecture.

Introduction

The separation of actinides (U, Np, Pu, Am, and Cm) from fission products (especially actinides(III) from lanthanides(III)) is a key step in the reduction of radiotoxicity and thermal emissions of ultimate nuclear waste. Light actinides (U and Pu) are currently separated industrially from the final waste by solvent extraction process (PUREX) and recycled after their conversion to produce new fuel. Minor actinides (Np, Am, Cm) are also potential fissile materials that could be recovered and recycled along with major actinides in fast neutron reactors (Gen IV reactors).[1] Recycling of minor actinides will also decrease the long-term radiotoxicity of the ultimate wastes. This concept, called homogeneous recycling of actinides, is one of the strategies being considered for future radioactive-waste management.[2] In this field, the group actinides extraction (GANEX) solvent extraction process is currently being intensively studied.

One of the main challenges of the GANEX process is to develop new solvating ligands that can selectively extract major and minor actinides together without affinity towards fission products. The separation of light actinides (U, Np, and Pu) from fission products can be achieved by exploiting the greater affinity of the higher oxidation states of the light 5f elements to hard Lewis bases (according to the Pearson Hard Soft Acid Base (HSAB) classification),[3] to form largely electrostatic bonds with alkylamide or alkylphosphate ligands (i.e., tri-*n*-butyl phosphate).[4] However transplutonium actinides (Am^{III} and Cm^{III}) and lanthanide(III) cations display very similar physicochemical properties.[5] Nevertheless, previous studies have shown that soft sulfur,[6] and nitrogen donors like tridentate N-donor aromatic cores, are efficient extractants for An^{III}/Ln^{III} separations because they are expected to form bonds with a slightly greater covalent character with actinides than with lanthanides.[4]

Considering the specific physicochemical properties of minor and major actinides, our strategy deals with the development of new bitopic extractants that combine amide groups and aza-aromatic rings as complementary functional units. Amide groups with hard-oxygen donors are expected to improve the extraction of light actinides (U, Np, Pu) from a highly acidic medium, whereas, aromatic soft nitrogen rings should achieve An^{III}/Ln^{III} selectivity. Our groups have recently reported the ability of bitopic terpyridine-based ligands to separate U^{VI}, Pu^{IV}, Am^{III}, Cm^{III}, and Np^{V-VI} by solvent extraction with some encouraging selectivity for actinides versus lanthanides.[7] However, the extraction efficiency for Am^{III} remains too weak for development at an industrial scale.

To improve the design of our ligands, we thought of replacing the central pyridine moiety of the terpyridine sequence by either a 1,10-phenanthroline or a 1,3,5-triazine unit bearing a variable group at the C2 center (Figure 1). 1,10-Phenanthroline was chosen for its rigidity and the juxtaposition of two ni-

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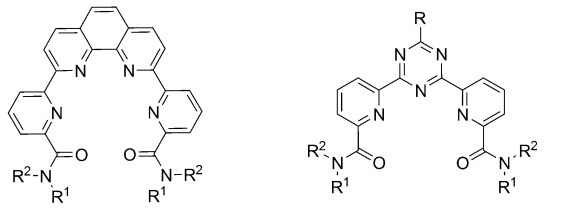
trogen donor atoms, which are known to thermodynamically favor complexation properties.[8] Central triazine rings were selected to lower the ligand affinity towards protons compared with the pyridine heterocycle, and thus favor metal complexation in a highly acidic medium.[9] In this field, nitrogen-donor aromatic bases such as 2,2′:6′2″-terpyridine (tpy) and triazine derivatives, in particular 2,6-di(5,6-dialkyl-1,2,4-triazin-3-yl)pyridine (Rbtp), 2,4,6-tri(pyridin-2-yl)-1,3,5-triazine (tptz), and 2-amino-4,6-di(pyridin-2-yl)-1,3,5-triazine (adptz), have already been studied as interesting ligands.[10,11]

In the present study, we report the synthesis and solvent extraction properties of new bitopic dipicolinamide *N,O*-ligands in [1,10]-phenanthroline and 2-substituted-1,3,5-triazine series (Figure 1). In the latter triazine series, we sought to explore the possibility of introducing variable substituents at the C2 position of the central heterocycle ring, which should shed light on the electronic effects on the extraction efficiency of poly-aza-heterocycle ligands.



1a $R^1 = R^2 = C_2H_5$
1b $R^1 = C_2H_5$, $R^2 = C_6H_5$
1c $R^1 = R^2 = C_8H_{17}$
1d $R^1 = C_6H_{13}$, $R^2 = C_6H_5$

2 R = NH_2, **3** R = C_6H_5, **4** R = CF_3
a, $R^1 = R^2 = C_2H_5$
b, $R^1 = C_2H_5$, $R^2 = C_6H_5$
c, $R^1 = R^2 = C_8H_{17}$

Figure 1. Structure of new phenanthroline- and triazine dipicolinamide-based ligands.

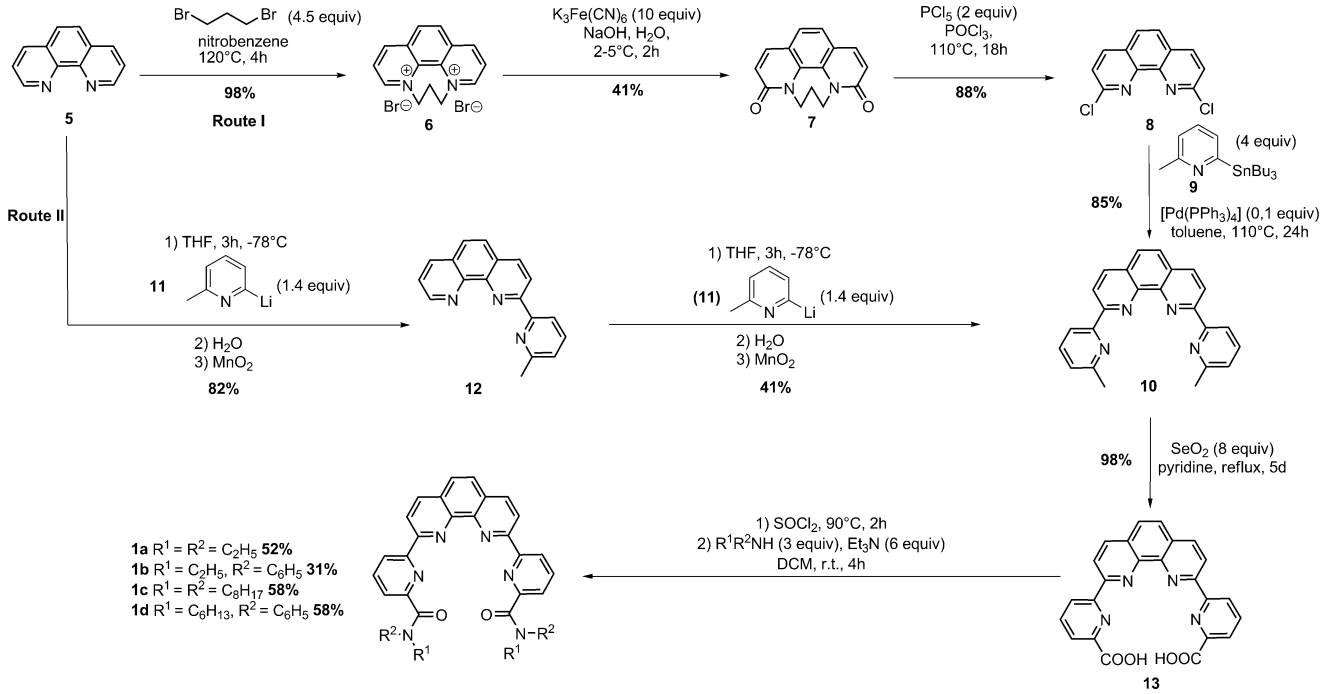
Results and Discussion

Ligand synthesis

The first challenge of this work was to develop fast and efficient routes to produce targeted new bitopic ligands. Although only a few limitations were expected in the preparation of 2,9-di(6-picolin-2-yl)-phenanthroline derivatives, the synthesis of 2-substituted-4,6-di(6-picolin-2-yl)-1,3,5-triazines was far from obvious due to the limited sets of methods describing the synthesis of non-symmetrical 2,4,6-substituted derivatives in the literature.[12]

Phenanthroline-based extractants

First, four new dipicolinamide phenanthroline-based ligands were synthesized following two different routes from commercially available 1,10-phenanthroline **5** (Scheme 1). Route I involves a conventional Stille coupling reaction from 2,9-dichlorophenanthroline **8** obtained in 3 steps according to a literature procedure.[13] Ammonium intermediate **6**, formed by adding a large excess of 1,3-dibromopropane to phenanthroline **5** in nitrobenzene, was oxidized by using $K_3[Fe(CN)_6]$ in basic aqueous solution to give the diketone **7** in 38% overall yield. 2,9-Dichlorophenanthroline **8** was then obtained in 88% yield by treating the diketone **7** with PCl_5 in $POCl_3$ at 110 °C. 2-(tributylstannyl)-6-picoline **9**, prepared from 6-picoline by a usual stannylation procedure,[14] was subsequently treated with dichloride **8**, dissolved in toluene, in the presence of



Scheme 1. Routes to the synthesis of the phenanthroline-based ligands **1a–d**.

$[Pd(PPh_3)_4]$ as a catalyst. Following this procedure, the 2,9-di(6-picolin-2-yl)-1,10-phenanthroline **10** was isolated in 85% yield. Despite the moderate yield of the oxidation step giving the ketone **7** from **6**, compound **10** could be relatively easily prepared on a multigram scale.

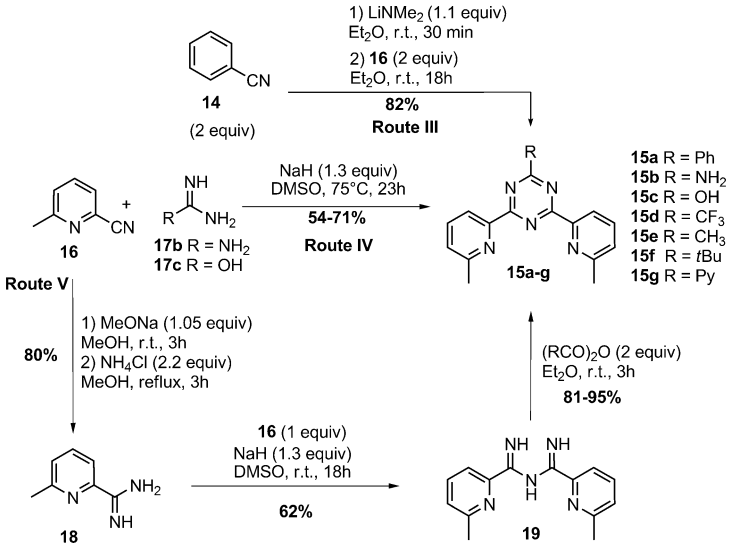
Alternatively, the synthesis of dipicoline phenanthroline **10** was envisioned in a shorter route (two reaction steps) from 1,10-phenanthroline (Route II) following a similar procedure described earlier by Sauvage and co-workers in the pyridine series.[15] A first picoline residue was directly introduced on the 1,10-phenanthroline **5** by reaction of a slight excess of the 2-picoline-lithium reagent **11** and, re-aromatization, after hydrolysis, of the resulting mono-substituted intermediate formed with MnO_2. The same procedure repeated from the resulting mono-substituted phenanthroline **12** led to the expected dipicoline compound **10** in 34% overall yield. In this reaction sequence, the 2-picoline-lithium **11** was generated in situ from the 2-bromo-6-picoline by halogen–metal exchange with *n*-BuLi at −78 °C. Although disubstituted phenanthroline **10** is advantageously accessible by Route II in only two steps, unfortunately, in our hands, this procedure cannot be scaled up at multigram scale because the second arylation reaction proceeded with a significant decrease in yield. Furthermore, attempts at the direct diarylation organo-coupling in the presence of almost 2 equivalents of picoline-lithium reagent **11** also failed.

We thus pursued our investigation by the oxidation of dipicoline phenanthroline **10** in the presence of a large excess of SeO_2 in pyridine affording the expected diacid **13** in an almost quantitative manner after 5 days, whereas a Jones oxidation using CrO_3 in sulfuric acid solvent did not result in the bis-oxidation of the dipicoline precursor **10**.

From the 6,6′-(1,10-phenanthrolin-2,9-diyl)-2,2′-dipicolinic acid **13**, access to two series of dipicolinamide phenanthroline ligands **1a–d** bearing two identical *N*-alkyl groups, or an alkyl and an aryl groups, was pursued. For this purpose a conventional peptide coupling procedure was used involving activation of dicarboxylic acid **13** as acid chloride, by $SOCl_2$ treatment, prior to adding 2 equivalents of the corresponding amine reagent in the presence of Et_3N in CH_2Cl_2. The four new dipicolinamide phenanthroline ligands **1a–d** were then isolated after flash chromatography on silica gel in 52, 31, 58, and 58% yields, respectively.

Triazine-based extractants

Over the past 10 years, increasing attention has been paid to pyridinyl-substituted triazine ligands and their complexes, mostly due to their promising photophysical properties.[16] Among them, particular interest has been focused on symmetric 2,4,6-tris-pyridine-1,3,5-triazine (TPTZ) ligands.[17] However, heterocycle sequences containing a non-symmetrically substituted triazine ring have been rarely studied mainly because of the lack of a general efficient method to facilitate their access.[12] Nevertheless, a few derivatives such as 2-amino-,[18] 2-hydroxy-,[18b] and 2-aryl-4,6-di(pyridin-2-yl)-1,3,5-triazine[19] have been described in the literature from a common 2-cyano-pyridine precursor and the procedures used were logically evaluated to reach targeted 2-substituted-4,6-di(6-picolin-2-yl)-1,3,5-triazine derivatives **15a–g** from the 2-cyano-6-picoline precursor (Scheme 2). As expected, Route III successfully afforded the 2-phenyl-triazine derivative **15a** (R = Ph) in 82% yield, by treating 2-cyano-picoline **16** (2 equivalents) with the lithium amidine salt of benzonitrile **14**, generated in situ from benzonitrile and lithium dimethylamine (2 M in THF) in Et_2O.[19] Route IV, proposed by Wieprecht for the preparation of 2-amino- and 2-hydroxy-dipyridinyltriazine derivatives,[18a] provided the corresponding dipicoline triazine analogues **15b** (R = NH_2) and **15c** (R = OH) in 71 and 54% yield, respectively, by reaction of the corresponding amidine (e.g., guanidine for amino- and urea for hydroxy-derivatives) with 2 equivalents of 2-cyano-picoline **16**.



Scheme 2. Synthesis of the 1,3,5-triazine-based 4,6-dipicoline derivatives **15a–g**.

Despite the possible access to triazines **15a** and **15b–c** by Routes III and IV, respectively, unfortunately, both pathways are limited by the poor diversity of commercially available reagents (nitriles and amidines) and therefore cannot be extended further to a large variety of 2-substituted-4,6-di(6-picolin-2-yl)-1,3,5-triazines. For instance, procedure IV applied with trifluoroacetamidine reagent gave the corresponding 2-trifluoromethyl-4,6-di(6-picolin-2-yl)-1,3,5-triazine **15d** in a disappointingly low yield (6%).

To develop a general method to access di(6-picolin-2-yl)-1,3,5-triazines bearing variable groups at the C2 position, we first investigated Pd-catalyzed cross-coupling methodologies, widely applied to trichloro-*s*-triazine or 2,4-dichloro-6-methoxy-*s*-triazine precursors.[20] However, in our hands, coupling reactions using the 2-picoline metallic reagents in Stille, Suzuki–

Miyaura, and Negishi processes failed to produce the disubtituted target compounds in good yield (i.e., 6% by Stille coupling).

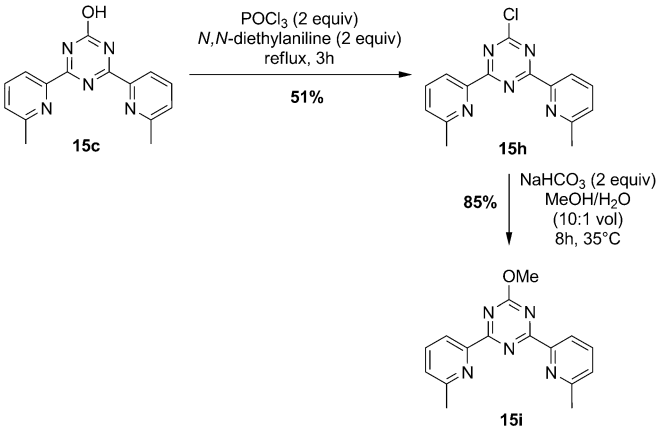
Finally, Route V was found to be the best way to reach our goal and was successfully extended to prepare 2-substituted-4,6-dipicoline 1,3,5-triazines **15a–g**. The strategy was inspired by a procedure described by Stamford and Schaefer[21] in 1965 providing access to 2-, 4-, and 6-substituted-1,3,5-triazines by treatment of acetic anhydride with trichloromethyltriazapentadiene intermediates. The preparation of the transient key-species 2,4-di(6-picolin-2-yl)-1,3,5-triazapentadiene **19** was carried out in two steps from the readily available 2-cyano-6-picoline **16** as shown in Scheme 2. Cyano-picoline **16** was first converted into the corresponding carboxamidine **18** in 80% yield by treatment with sodium methoxide in methanol at room temperature prior to the addition of ammonium chloride.[22] The carboxamidine **18** was then treated with another equivalent of 2-cyano-6-picoline **16** in the presence of NaH, in DMSO at room temperature, to give the expected 2,4-di(6-picolin-2-yl)-1,3,5-triazapentadiene **19** in 62% yield. Following this process, a number of C2-substituted dipicoline triazines can be obtained from the same 1,3,5-triazapentadiene precursor **19** depending on available anhydride reagents. To illustrate the purpose, five 2-substituted-4,6-di(6-picolin-2-yl)-1,3,5-triazines **15a–g** were formed (Table 1) using alkyl- (entries 4 and 5), heteroalkyl- (entry 3), aryl- (entry 1), and heteroaryl-anhydrides

Table 1. Route V: Synthesis of 2-substituted-4,6-di(6-picolin-2-yl)-1,3,5-triazines **15**.

Entry	Anhydride	Product	Yield [%]
1	$(C_6H_5–CO)_2O$	**15a** R = Ph	93
2	$(CH_3O–CO)_2O$	**15c** R = OH	81
3	$(CF_3–CO)_2O$	**15d** R = CF_3	86
4	$(CH_3–CO)_2O$	**15e** R = CH_3	95
5	$(t$Bu–$CO)_2O$	**15f** R = *t*Bu	90
6	$(C_5H_4N–CO)_2O$	**15g** R = C_5H_4N	82

(entry 6). All compounds were formed as a sole reaction product isolated in good yields (81 to 95%) after purification by chromatography on silica gel. The later procedure takes advantage of the fact that when the corresponding anhydride is not commercially available (i.e., picolinic anhydride), simple existing synthetic methods can be used to prepare it.[23]

The use of dimethyldicarbonate (Table 1, entry 2), expected to introduce a methoxy group at the C2 position of the triazine, gave the hydroxytriazine derivative **15c**, isolated as the sole product of the reaction (81% yield). This result prompted us to overcome the problem by using a halogeno intermediate. Thus, treating hydroxytriazine **15c** in phosphoryl chloride heated at reflux in the presence of *N*,*N*-diethylaniline for 3 h, led to the formation of the 2-chloro-4,6-di(picolin-2-yl)-1,3,5-triazine **15h** in 51% yield (Scheme 3).[24] Triazine chloride **15h** is quite sensitive to hydrolysis and must be readily engaged in the next step to avoid its degradation.

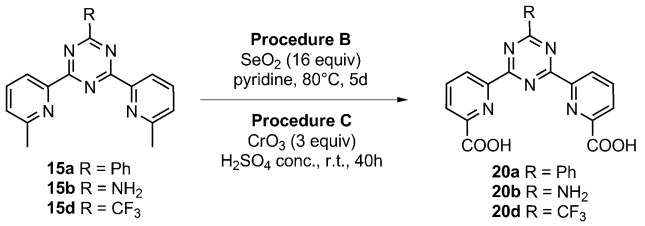


Scheme 3. Preparation of 2-methoxy-4,6-(6-picolin-2-yl)-1,3,5-triazine **15i** from hydroxytriazine **15c**.

The substitution of the chlorine group on **15h** by a methoxy group proceeded after addition of $NaHCO_3$ (2 equivalents) in a MeOH/H_2O mixture (v/v = 10:1) at 35 °C, allowing complete conversion into the 2-methoxy-triazine **15i** in 85% yield.

To summarize, Routes III, IV, and V have enabled the preparation of nine new di(6-picolin-2-yl)-1,3,5-triazine derivatives bearing different substituents at the C2 position in good yields. It has to be noted that obviously the developed procedure should allow the preparation of trisubtituted 1,3,5-triazine derivatives bearing differentiated groups at 2, 4, and 6 positions.

With a view to obtain the corresponding dicarboxylic acids **20a–i**, two oxidation procedures were evaluated on the dipicolinyl-triazine derivatives **15a–i**: in the presence of SeO_2 or through a Jones procedure using CrO_3 in sulfuric acid (procedures **B** and **C**, respectively, Scheme 4). Both methods were



Scheme 4. Oxidation of 2-substituted-4,6-(dipicolin-2-yl)-1,3,5-triazines **15**.

compared and the results are summarized in Table 2. Whereas di-oxidation of dipicoline phenanthroline **10** by SeO_2 was completed in pyridine heated at reflux (98% yield, see Scheme 2), triazine substrates appeared much more sensitive depending on the nature of the C2 substituent. Success was encountered with SeO_2 when the reactions were run at 80 °C (Table 2, entries 1 and 7, **15a** R = Ph and **15d** R = CF_3) avoiding the substantial degradation that occurs above this temperature.

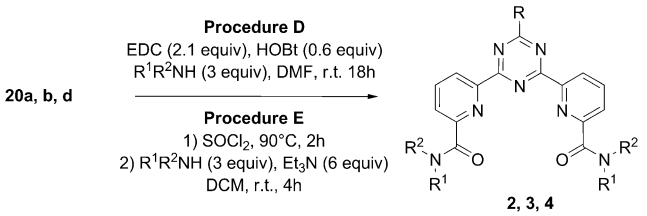
However, selenium dioxide failed to oxidize electron-donating 2-substituted triazines (Table 2, entries 5, 9 and 11; **15c** R = OH, **15h** R = Cl and **15i** R = OMe, respectively) and CrO_3 was

Table 2. Results of oxidation procedures on **15a–i.**

Entry	Substrate **15a–i**	Product	Oxidation procedure	Yield [%] **20a–i**
1	**15a** R = Ph	**20a**	**B**	91
2			**C**	–
3	**15b** R = NH_2	**20b**	**B**	–
4			**C**	76
5	**15c** R = OH		**B**	Not attempted
6			**C**	–
7	**15d** R = CF_3	**20d**	**B**	81
8			**C**	Not attempted
9	**15h** R = Cl		**B**	–
10			**C**	–
11	**15i** R = OMe		**B**	–
12			**C**	Not attempted

only efficient at room temperature on the 2-amino-di(6-picolin-2-yl)-1,3,5-triazine **15b** (entry 4; R = NH_2) giving the corresponding amino-triazine dicarboxylic acid **20b** in a good 76% yield.

Finally, the targeted dipicolinamide triazine ligands were obtained from the corresponding dipicolinic acids **20a**, **20b**, and **20d** by using two peptide-coupling procedures (Scheme 5). The access to the dipicolinamide triazines **2a–c**, in the amino-



Scheme 5. Procedures for amide formation on triazine ligands.

triazine series, was only performed in moderated yields following an activation of the diacid **20b** with a mixture of *N*-ethyl-*N*′-(3-dimethylaminopropyl)carbodiimide (EDC) and 1-hydroxybenzotriazole (HOBt; procedure **D**), in the presence of amine partners (diethylamine **a**, ethylphenylamine **b** or dioctylamine **c**; Table 3; entries 1–3). The poor yield in the dipicolinamide triazine **2c** (10%) was mostly due to some purification difficulties on silica gel due to the high lipophilicity of dioctylamine groups. However, the method previously used in the phenanthroline series provided the dipicolinamide triazine ligands **3a–c** and **4a–c** in better yields from diacids **20a** and **20d**, respectively (Table 3; entries 4–8). For this purpose, the latter dicarboxylic acids were dissolved in $SOCl_2$, 2 h at 90 °C, prior to adding the amine partners in the presence of Et_3N (procedure **E**).

Eight new dipicolinamide triazine-based ligands **2a–c**, **3a–c** and **4a**,**b** were obtained in 44 to 58% yields.

Table 3. Amide formation on 6,6′-(2-substituted-1,3,5-triazine-4,6-diyl)-2,2′-dipicolinic acid.

Entry	Substrate	Triazine ligand	R	R^1/R^2	Procedure	Yield [%][a]
1		**2a**	NH_2	ethyl/ethyl	**D/E**	58/0
2	**20b**	**2b**	NH_2	ethyl/phenyl	**D**	54
3		**2c**	NH_2	octyl/octyl	**D**	10
4		**3a**	Ph	ethyl/ethyl	**E**	44
5	**20a**	**3b**	Ph	ethyl/phenyl	**E**	59
6		**3c**	Ph	octyl/octyl	**E**	56
7	**20d**	**4a**	CF_3	ethyl/ethyl	**E**	55
8		**4b**	CF_3	ethyl/phenyl	**E**	58

[a] Purified product.

Solvent-extraction studies

Preliminary stability studies in an alcohol/water medium

Prior to extraction studies, ligand stability was evaluated in an alcohol/water medium (MeOH/H_2O) by UV/Visible and NMR spectroscopic analyses recorded for each diethylamide derivatives **2a**, **3a**, **4a**, and **1a**. Whereas no change was observed in phenanthroline, in the amino-triazine and phenyl-triazine series, the UV profile of both trifluoromethyl-triazine ligands **4a** and **4b** varied during the experiment time. A kinetic study on **4a** using ^1H and ^{19}F NMR spectroscopy in deuterated MeOD/D_2O medium confirms this phenomenon with appearance of two new products. The similar chemical shifts of both formed species suggested a similar structure (see data in the Supporting Information). The nature of each species was determined by ESI-MS spectroscopy (see data in the Supporting Information) indicating that, in a MeOH/H_2O medium, regioselective nucleophilic addition of a methoxy or a hydroxyl residue occurred on the C2 aromatic bond activated by the trifluoromethyl group (Figure 2). Consequently, these medium-sensitive ligands cannot be useful in the extraction evaluations.

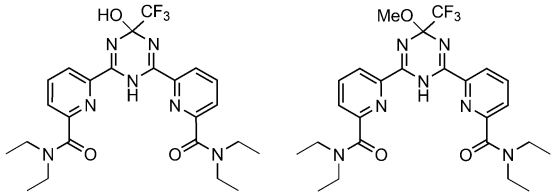


Figure 2. Byproducts obtained when **4a** stands in a MeOH/H_2O medium.

Extraction tests on Am^{III}, Cm^{III}, Eu^{III}, and Pu^{IV}

The extraction of actinides at different oxidation states ($^{241}Am^{III}$, $^{244}Cm^{III}$, and $^{239-240}Pu^{IV}$) from a 3 M HNO_3 solution was measured with the lipophilic ligands **1c**, **1d**, **2c**, and **3c** dissolved in *n*-octanol. Unfortunately, other ligands are not soluble enough in *n*-octanol to be evaluated in such experiment. $^{152}Eu^{III}$ extraction was also tested to establish ligand selectivity towards lanthanides. The extraction data are summarized in Table 4 and compared with those of *N,N,N′,N′*-tetraoctyl-6,6′-2,2′:6′,2″-terpyridine diamide (**te-tpyda**). This ligand, previously studied in our group,[7] was chosen as a reference due to its comparable molecular structure.

Table 4. Distribution coefficients of actinides and Eu^{III} by diamidopolynitrogen ligands and related separation factors.[a]

Extractant	**1c**	**1d**	**2c**	**3c**	**te-tpyda**[7]
$[HNO_3]_{eq}$ [M]	2.6	2.6	2.6	2.6	2.5
$D_{Eu(III)}$	6.3×10^{-3}	0.091	3.5×10^{-3}	3.4×10^{-3}	1.1×10^{-3}
$D_{Am(III)}$	0.17	1.8	0.043	0.042	4.6×10^{-3}
$D_{Cm(III)}$	0.07	0.74	0.013	0.016	2.6×10^{-3}
$D_{Pu(IV)}$	2.2	14.8	0.47	0.18	0.35
$SF_{Am/Eu}/SF_{Pu/Eu}$	27/350	20/162	12/157	12/53	5/320

[a] Extractant 0.01 mol L^{-1} in *n*-octanol; cations as traces; $[HNO_3]_{aq.}^{init} = 3$ mol L^{-1}, 25.0 °C)

Results shown that Pu^{IV} is the element most efficiently extracted ($0.2 < D_{Pu(IV)} < 15$) by all ligands and that Am^{III} and Cm^{III} are 10 to 400 times less extracted than Pu^{IV}. This higher affinity towards Pu^{4+} could be related to the charge of the cation. The replacement of the central pyridine by a triazine unit leads to better extraction of Am^{III} and Cm^{III} (10 fold higher than with **te-tpyda**) whereas affinity towards Eu^{III} and Pu^{IV} remains similar. A positive effect on Pu^{IV} extraction is also observed when the triazine core is functionalized by a donor group ($R = NH_2$ vs. Ph, see Scheme 5). The presence of a phenanthroline central unit leads to better extraction of all actinides (for example, $D_{Pu} = 2.2$ and 14.8 vs. 0.35 for **te-tpyda**). This feature could be explained by an increasing number of accessible nitrogen donor atoms (4 for dipicoline phenanthroline instead of 3 for the terpyridine sequence) associated with a suitable preorganization of the 2,9-di(6-picolin-2-yl)-[1,10]-phenanthroline architecture, inasmuch as the *cis*-locked [1,10]-phenantroline motif is already favorable for cation complexation.[14]

Substituting an ethyl chain for a phenyl group on each amide function, significantly enhanced the cation extraction efficiency as observed with **1c** and **1d**. The positive effect of phenyl groups, known as "anomalous aryl strengthening", has already been observed with bidentate organophosphorous reagents such as $R_2P(O)–CH_2–P(O)R_2$.[25] It was supposed that replacing an R alkyl group by a conjugated group, such as a phenyl, in the methylene bisphosphine favors electron delocalization through the carbamide functions by enhancing the donating effect from the lone pair of the nitrogen to the oxygen atom. Our results represent a striking illustration of the contribution of an aryl group, which shed light on the influence of the hard O-amide group in combination with N-donor atoms on the selection of the metal cation.

Am^{III}/Eu^{III} selectivity with a dipicoline triazine core is almost 2-fold higher than with a pyridine one ($SF_{Am/Eu}$ over 10 for **2c** and **3c** vs. 5 for **te-tpyda**). The presence of the phenanthroline moiety also enhances the Am^{III}/Eu^{III} selectivity ($SF_{Am/Eu} = 26$ and 19 for **1c** and **1d**, respectively). These interesting separation factors are comparable to the value of PTA presented by Yaita ($SF_{Am/Eu} = 20$, 1 M HNO_3),[26] and confirm the interest of dipicolinamide phenanthroline structures for the design of a powerful GANEX process extractant.

To check the stoichiometry of the extracted complexes, studies were performed with a representative molecule of the series, namely **1d**. Only the variation in Am and Pu extraction with the extractant concentration was measured as previous studies with similar molecules (diamidoterpyridines) have been already reported with Pu^{IV}, Am^{III}, and Cm^{III}, all consistent with a 1:1 stoichiometry M ligand.[7] The acidity of the aqueous phase was 2.6 M after equilibrium, which gives a distribution of HNO_3 of 0.16 (mainly due to the partition between aqueous HNO_3 and *n*-octanol), which is consistent with previous data.[27] The range of ligand concentration was from 10^{-4} to 10^{-2} M (limit of solubility in *n*-octanol).

The plot of the logarithms of D_{Am} and D_{Pu} as a function of the logarithm of the ligand concentration is presented in Figure 3. As anticipated, the slopes close to 1, 0.95, and 1.06, respectively, imply a 1:1 species for the extracted complexes.

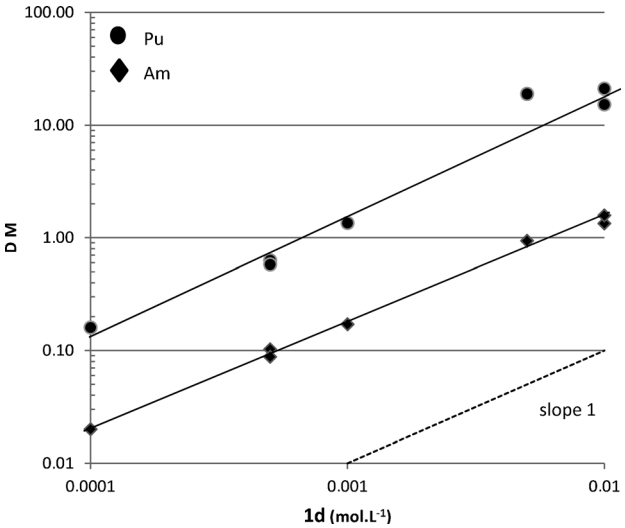


Figure 3. Extraction of Am^{III} and Pu^{IV} by **1d** in *n*-octanol. $T = 25$ °C; ^{239}Pu and ^{241}Am as traces.

Extraction tests on U^{VI} and $Np^{V–VI}$

Regarding the potential of **1c** and **1d** ligands in a new GANEX extraction process, two complementary experiments were carried out to determine their ability to extract $^{238}U^{VI}$ and $^{237}Np^{V–VI}$ from a 3 M nitric acid solution. Data are presented in Table 5.

Results show that **1c** and **1d** are both able to extract ^{237}Np and $^{238}U^{VI}$ with good distribution coefficients ($D > 2$ for uranium and > 10 for neptunium). Unfortunately, formation of a third phase was observed during uranium extraction with **1d** due to its poor solubility in *n*-octanol. However, the ligands

Table 5. Distribution coefficients of $Np^{V–VI}$ and U^{VI} by diamidopolynitrogen ligands.[a]

Extractant	**1c**	**1d**
$[HNO_3]_{eq}$ [M]	2.6	2.6
$D_{Np(V–VI)}$	11	16.6
$D_{U(VI)}$	1.9	> 2[b]

[a] Extractant: 0.01 mol L^{-1} in *n*-octanol; $[^{237}Np^{V–VI}] = 6.5\times10^{-4}$ mol L^{-1} or $[^{238}U^{VI}] = 4.10^{-3}$ mol L^{-1}; $[HNO_3]_{aq.}^{init} = 3$ mol L^{-1}, 25.0 °C. [b] 3rd Phase formation: $[U]_{aq,eq} = 10\%\ [U]_{ini}$.

ability to extract neptunium from a mixture of V and VI oxidation states is of particular interest as both are found in fuel dissolution solutions. These results confirm the interest in dipicolinamide phenanthroline sequences to explore a GANEX-based process.

Conclusion

In this study, we have reported the synthesis of 12 new bitopic molecules designed for the GANEX process: 6,6′-(1,10-phenantrolin-2,9-diyl)-2,2′-dipicolinamides **1a–1d** and 6,6′-(2-substituted-1,3,5-triazine-4,6-diyl)-2,2′-dipicolinamides **2a–4b**. Improved synthesis pathways were developed to prepare these molecules. Obviously, the developed procedure to reach 4,6-dipicolinamide 1,3,6-triazines should allow the preparation of number of trisubstituted 1,3,5-triazine derivatives bearing differentiated groups at either the 2-, 4-, and 6 positions.

Four of these lipophilic molecules **1c**, **1d**, **2c**, and **3c** were retained for extraction investigations mostly because of their good solubility in *n*-octanol solvent. Unfortunately, trifluoromethyl-triazine-based ligands **4a** and **4b** were rejected for this purpose due to their sensitive electrophilic behavior in an alcohol/water medium.

Extraction results show that these new ligands can extract actinides at different oxidation states from a highly acidic medium (3 M HNO_3) with the order of affinity $Pu^{IV} > Am^{III} > Cm^{III}$ whereas Eu^{III}, representative of lanthanides(III), remains in the aqueous phase. Introduction of a donor group on the poly-nitrogen ring sequence provides a better extraction of Pu^{IV} as already described with amidoterpyridines.[7] The combination of a rigid pre-organized conformation and an increasing number of nitrogen-donor atoms presented by the dipicolinamide phenanthroline series leads to a better extraction efficiency in comparison with known dipyridinyl-triazine- or terpyridine-based ligands. Furthermore, compound **1d** appears the best candidate for the group separation of actinides from a spent fuel dissolution solution. The presence of a phenyl group on amide functions leads to higher performances despite a decreasing solubility in the organic phase, which limits its exploitation in the GANEX process. The introduction of lipophilic chains on the phenanthroline core could thus be proposed to improve the design of more efficient extractants in this series and studies are now currently ongoing in our laboratory.

Experimental Section

Synthesis of the ligands

General: Solvents were purified and dried by standard methods prior to use. *n*-BuLi (2,5 M in hexanes) was purchased from ACROS. NaH (60% dispersion in mineral oil) was purchased from ALDRICH and was washed with petroleum ether prior to use. All reactions were monitored by TLC on commercially available pre-coated plates (Kieselgel 60 F_{254}) and the products were visualized with a Mohr solution (10 g of $FeSO_4$ in 100 mL of H_2O). Kieselgel 60, 230–400 mesh (Merck) or neutral alumina was used for column chromatography with compressed air. ^1H and ^{13}C NMR spectra were recorded on a Bruker AC 300 MHz using the deuterated solvent signal as lock. Chemical shifts (δ) are given in ppm and coupling constants (J) in Hz with the following abbreviation for signal multiplicity: s (singlet), d (doublet), dd (doublet of doublets), dt (doublet of triplets), t (triplet), td (triplet of doublets), q (quartet), qd (quartet of doublets), quint (quintuplet), st (sextuplet), m (multiplet), and further qualified as b (broad). HRMS (EI and ESI) were measured on a MAT95XL Thermofinnigan spectrometer and were performed at the "Centre Commun de Spectrométrie de Masse", Université Claude Bernard Lyon 1, France. HRMS (MALDI) were measured on a MALDI-TOF-TOF (Autoflex III from Bruker) and were performed at INRA in Nantes.

2,9-Di(6-picolin-2-yl)-1,10-phenanthroline (10): *Route I*: A mixture of 2,9-dichloro-1,10-phenanthroline (685 mg, 2.7 mmol), 2-tributylstannyl-6-picoline (4.2 g, 4.0 equiv), $[Pd(PPh_3)_4]$ (322 mg, 0.1 equiv), and freshly distilled and degassed toluene (100 mL) was heated at reflux for 24 h under argon. The solvent was evaporated and the residue was dissolved in CH_2Cl_2. The resulting solution was then filtered on Celite® and successively washed with water, an aqueous solution of KF, and an aqueous saturated solution of $NaHCO_3$. The organic phase was dried with Na_2SO_4, filtered, and the solvent evaporated. The crude product was then dissolved in a small amount of CH_2Cl_2 and the resulting white precipitate was filtered. The filtrate was evaporated and purified by chromatography on silica gel (eluent PE (Petroleum Ether)/AcOEt 50:50). The expected phenanthroline **10** was obtained in 85% yield (850 mg) as a yellow powder. M.p. 223 °C; ^1H NMR ($CDCl_3$): $\delta = 8.96$ (d, $^3J = 8.4$, 2H, H_3), 8.91 (d, $^3J = 7.8$, 2H, $H_{3'}$), 8.41 (d, $^3J = 8.4$, 2H, H_4), 7.90 (t, $^3J = 7.8$, 2H, $H_{4'}$), 7.86 (s, 2H, H_5), 7.29 (d, $^3J = 7.8$, 2H, $H_{5'}$), 2.73 ppm (s, 6H, $2CH_3$); ^{13}C NMR ($CDCl_3$): $\delta = 157.8$ (2Cq), 156.1 (2Cq), 155.5 (2Cq), 145.6 (2Cq), 137.2 ($2C_{4'}$), 137.2 ($2C_4$), 129.0 (2Cq), 126.6 ($2C_5$), 123.8 ($2C_{5'}$), 120.6 ($2C_3$), 119.2 ($2C_{3'}$), 24.7 ppm ($2CH_3$); HRMS (EI): *m/z* calcd for $C_{24}H_{18}N_4$: 362.1531 $[M]^+$; found: 362.1533. Compound **10** was also obtained by Route II: See the Supporting Information.

6,6′-(1,10-Phenanthrolin-2,9-diyl)-2,2′-dipicolinic acid (13): SeO_2 (1.96 g, 8.0 mmol, 8 equiv) was added to a solution of **10** in pyridine (790 mg in 60 mL). After 5 days of heating at reflux, the hot crude product was filtrated through a pad of Celite that was washed with methanol. The filtrate was allowed to warm to RT and a part of solvents were evaporated. Then, dichloromethane was added and the expected product **13** was isolated by filtration in 98% yield (0.91 g) as a yellow powder. M.p. > 230 °C; ^1H NMR (DMSO): $\delta = 9.21$ (dd, $^3J = 7.6$, $^4J = 0.8$ Hz, 2H), 9.00 (d, $^3J = 8.4$ Hz, 2H), 8.72 (d, $^3J = 8.4$ Hz, 2H), 8.33 (t, $^3J = 7.6$ Hz, 2H), 8.22 (d, $^3J = 7.6$ Hz, 2H), 8.12 ppm (s, 2H, H_5); ^{13}C NMR (DMSO): $\delta = 166.0$ (2CO), 155.4 (2Cq), 154.1 (2Cq), 149.1 (2Cq), 145.0 (2Cq), 139.1 ($2C_{4'}$), 137.6 ($2C_4$), 129.2 (2Cq), 127.1 ($2C_5$), 125.3 ($2C_{5'}$), 124.6 ($2C_{3'}$), 120.5 ppm ($2C_3$); HRMS (ESI^+): *m/z* calcd for $C_{24}H_{15}N_4O_4$ 423.1091 $[M+H]^+$; found: 423.10936

6-Picolinyl-2-carboxamidine (**18**): 2-Cyano-6-picoline **16** (4.0 g, 34.90 mmol) was added to a solution of NaOMe (36.65 mmol, 1.05 equiv) in MeOH (40 mL). After 3 h at RT, NH_4Cl (4.19 g, 76.8 mmol, 2.2 equiv) was added in portions and the mixture was heated at reflux for 3 h. The NaCl formed was then filtered and the solvent evaporated. CH_2Cl_2 was added to the resulting crude product and the precipitate was filtered and dried to yield 80% of the expected carboxamidine **18** (3.76 g) as a white powder. M.p. 85 °C; ^1H NMR (DMSO): $\delta = 8.07$ (d, $^3J = 7.8$ Hz, 1H, H_3), 7.90 (t, $^3J = 7.5$ Hz, 1H, H_4), 7.48 (d, $^3J = 7.5$ Hz, 1H, H_5), 2.55 ppm (s, 3H, CH_3); ^{13}C NMR (DMSO): $\delta = 160.9$ (Cq), 157.6 (Cq), 146.9 (Cq), 137.7 (C_4), 126.2 (C_5), 119.0 (C_3), 23.9 ppm (CH_3); HRMS ($ESI+$): *m/z* calcd for $C_7H_{10}N_3$ 136.0869 $[M+H]^+$; found: 136.0867.

2,4-Di(6-picolin-2-yl)-1,3,5-triazapentadiene (19): NaH (1.5 equiv) was added in portions to a solution of 2-cyano-6-picoline **16**

(344 mg, 2.91 mmol, 1.0 equiv) and carboxamidine **18** (500 mg, 2.91 mmol, 1.0 equiv) in DMSO (6 mL). After stirring overnight at RT, CH_2Cl_2 was added and the mixture was washed with water, dried on Na_2SO_4, filtered, and the solvent evaporated. The crude product was purified by chromatography on silica gel (eluent: EP/AcOEt 80:20). The expected product **19** was obtained with 62% yield (456 mg) as a white powder. M.p.119 °C; ^{1}H NMR ($CDCl_3$): $\delta =$ 11.33 (b, 1H, NH), 9.56 (b, 2H, 2NH), 8.36 (d, $^3J = 7.8$ Hz, 2H, H_3), 7.72 (t, $^3J = 7.8$ Hz, 2H, H_4), 7.23 (d, $^3J = 7.8$ Hz, 2H, H_5), 2.66 ppm (s, 6H, $2CH_3$); ^{13}C NMR (DMSO): $\delta = 165.1$ (2Cq), 157.4 (2Cq), 151.5 (2Cq), 137.1 ($2C_4$), 124.7 ($2C_5$), 118.9 ($2C_3$), 24.4 ppm ($2CH_3$); HRMS (MALDI): *m/z* calcd for $C_{14}H_{16}N_5$ 254.1400 $[M+H]^+$; found: 254.1408.

General procedure A (Route V) to compounds 15a–i: Cyclization of 19 with an anhydride

The anhydride (2.0 equiv) was added in three portions to a vigorously stirred solution of triazapentadiene **19** at 0 °C in Et_2O (0.3 M). After 3 h at RT, the solvent was removed and the residue was dissolved in CH_2Cl_2, washed with NaOH (3 M) and water, dried on Na_2SO_4, filtered, and the solvent evaporated. The expected triazine was purified by flash chromatography on silica gel.

2-Phenyl-4,6-di(6-picolin-2-yl)-1,3,5-triazine (15a): Compound **15a** was obtained by the General Procedure **A** with triazapentadiene derivative **19** (200 mg, 0.73 mmol), benzoic anhydride (365 mg, 1.58 mmol, 2.0 equiv) in Et_2O (3 mL). The crude product was purified on flash chromatography (eluent: PE/AcOEt 10:90) to yield 93% of the expected triazine **15a** (231 mg) as a white powder. M.p. 176 °C; ^{1}H NMR ($CDCl_3$): $\delta = 8.81$ (dd, $^3J = 6.0$, $^4J =$ 1.5 Hz, 2H), 8.64 (d, $^3J = 7.8$ Hz, 2H), 7.84 (t, $^3J = 7.8$ Hz, 2H), 7.60 (m, 3H), 7.39 (d, $^3J = 7.8$ Hz, 2H), 2.79 ppm (s, 6H, $2CH_3$); ^{13}C NMR ($CDCl_3$): $\delta = 172.6$ (Ph-CqTz), 171.7 (2Cq), 159.4 (2Cq), 152.8 (2Cq), 137.1 ($2C_4$), 135.5 (Cq-Ph), 132.9 ($C_{4'}$), 129.3 ($2C_{2'}$), 128.6 ($2C_{3'}$), 126.2 ($2C_5$), 122.2 ($2C_3$), 24.6 ppm ($2CH_3$); HRMS (EI): *m/z* calcd for $C_{21}H_{17}N_5$: 339.1484 $[M]^+$; found: 339.1485. Compound **15a** was also obtained by Route III (see the Supporting Information).

2-Amino-4,6-di(6-picolin-2-yl)-1,3,5-triazine (15b): NaH was added in portions (2.5 mmol, 1.0 equiv) to a solution of 2-cyano-6-methylpyridine **16** (0.60 g, 5.1 mmol, 2.0 equiv) and guanidine hydrochloride (350 mg, 3.7 mmol, 1.4 equiv) in freshly distilled EtOH (10 mL). The mixture was then stirred for 2 h at RT and heated at reflux for 24 h under an Ar atmosphere. After cooling of the mixture to RT, the expected product was isolated by filtration and washed with water. The pure triazine **15b** was obtained in 77% yield (0.79 g) as a white powder. M.p. > 230 °C; ^{1}H NMR (DMSO): $\delta = 8.34$ (d, $^3J = 7.8$ Hz, 2H, H_3), 8.13 (s, 2H, NH_2), 7.97 (t, $^3J = 7.8$ Hz, 2H, H_4), 7.52 (d, $^3J = 7.8$ Hz, 2H, H_5), 2.59 ppm (s, 6H, $2CH_3$); ^{13}C NMR (DMSO): $\delta = 170.1$ (2Cq), 167.8 (NH_2-CqTz), 158.5 (2Cq), 152.4 (2Cq), 137.9 ($2C_4$), 126.2 ($2C_5$), 121.0 ($2C_3$), 24.0 ppm ($2CH_3$); HRMS (EI): *m/z* calcd for $C_{15}H_{14}N_6$ 278.1280 $[M]^+$; found: 278.1279.

For the synthesis of triazine **15c**, **15e**, **15f**, **15g**, **15h**, and **15i** see the Supporting Information.

2-Trifluoromethyl-4,6-di(6-picolin-2-yl)-1,3,5-triazine (15d): Compound **15d** was obtained by the General Procedure **A** with triazapentadiene derivative **19** (700 mg, 2.8 mmol), trifluoroacetic anhydride (1.1 g, 0.78 mL, 2 equiv) in Et_2O (5 mL). The crude product was purified on flash chromatography (eluent: PE/AcOEt 20:80) to yield 86% of the expected triazine **15d** (800 mg) as a whitish powder. M.p. 174 °C; ^{1}H NMR ($CDCl_3$): $\delta = 8.56$ (d, $^3J = 7.6$ Hz, 2H), 7.83 (t, $^3J = 7.6$ Hz, 2H), 7.42 (d, $^3J = 7.6$ Hz, 2H), 2.77 ppm (s, 6H, CH_3); ^{13}C NMR ($CDCl_3$): $\delta = 173.0$ (2Cq), 166.8 (q, $^{CF}J = 38.2$, CF_3-CqTz), 160.0 (2Cq), 151.0 (2Cq), 137.4 ($2C_4$), 127.3 ($2C_5$), 123.0 ($2C_3$), 118.8 (q, $^{CF}J = 275.3$, CF_3), 24.4 ppm ($2CH_3$); ^{19}F NMR ($CDCl_3$): $\delta =$ −71.91 ppm (s, CF_3); HRMS (MALDI): *m/z* calcd for $C_{16}H_{12}N_5F_3Na$: 354.0937 $[M+Na]^+$; found: 354.0952.

General procedure B: Triazine oxidation with SeO_2

SeO_2 (16 equiv) was added to a solution of triazine **15** in pyridine (0.05 M). After 5 days at 80 °C, the hot crude product was filtrated through a pad of Celite that was washed with methanol. The filtrate was allowed to warm to RT and a part of solvents were evaporated. Then, H_2O was added and the expected product was isolated by filtration and drying under vacuum.

6,6′-(2-Phenyl-1,3,5-triazine-4,6-diyl)-2,2′-dipicolinic acid (20a): Compound **20a** was obtained by the General Procedure **B** with triazine **15a** (600 mg, 1.8 mmol, 1.0 equiv), pyridine (45 mL), and SeO_2 (3.20 g, 28.3 mmol, 16.0 equiv) in 91% yield (0.62 g) as a white powder. M.p. > 230 °C; ^{1}H NMR (DMSO): $\delta = 8.93$ (m, 2H), 8.76 (dd, $^3J = 8.1$, $^4J = 1.5$ Hz, 2H), 8.32 (m, 4H), 7.73 ppm (m, 3H); ^{13}C NMR (DMSO): $\delta = 171.9$ (Ph-CqTz), 170.9 (2CO), 166.0 (2Cq), 153.0 (2Cq), 149.2 (2Cq), 138.9 ($2C_3$ or $2C_4$), 134.9 (Cq-Ph), 133.4 ($C_{4'}$), 129.1 ($2C_{3'}$), 128.9 ($2C_5$), 127.8 ($2C_{2'}$), 127.3 ppm ($2C_3$ or $2C_4$); HRMS (MALDI): *m/z* calcd for $C_{21}H_{13}N_5O_4Na$: 422.0860 $[M+Na]^+$; found: 442.0850.

6,6′-(2-Trifluoromethyl-1,3,5-triazine-4,6-diyl)-2,2′-dipicolinic acid (20d): Compound **20d** was obtained by the General Procedure **B** with triazine **15d** (500 mg, 1.5 mmol, 1.0 equiv), pyridine (37 mL), and SeO_2 (2.68 g, 24.2 mmol, 16.0 equiv) with 81% yield (473 mg) as a whitish powder. M.p. > 230 °C; ^{1}H NMR (DMSO): $\delta = 8.88$ (dd, $^3J = 6.4$, $^4J = 2.4$ Hz, 2H), 8.34 ppm (m, 4H); ^{13}C NMR (DMSO): $\delta =$ 171.8 (2Cq), 165.0 (2Cq), 164.4 (q, $^{CF}J = 37.0$ Hz, CF_3-CqTz), 151.6 (2Cq), 149.6 (2Cq), 139.2 ($2C_3$ or $2C_4$), 128.1 ($2C_5$), 127.9 ($2C_3$ or $2C_4$), 119.0 ppm (q, $^{CF}J = 275.0$ Hz, CF_3); ^{19}F NMR (DMSO): $\delta =$ −70.66 ppm (s, CF_3); HRMS (MALDI): *m/z* calcd for $C_{16}H_8N_5O_4F_3Na$: 414.0421 $[M+Na]^+$; found: 414.0421.

Procedure C: Triazine oxidation with CrO_3

6,6′-(2-Amino-1,3,5-triazine-4,6-diyl)-2,2′-dipicolinic acid (20b): CrO_3 (0.80 g, 8.1 mmol, 6.0 equiv) was added in 0.10 g portions over 3 h to a solution of amino-triazine **15b** (0.35 g, 1.3 mmol) in concentrated H_2SO_4 (10 mL) cooled to 0 °C. After complete addition of CrO_3, the mixture was stirred for 8 h at 0–5 °C, and 36 h at RT. The viscous reaction solution was then poured onto ice with stirring. The precipitated product was finally isolated by filtration, washed with water, and dried under vacuum to yield 61% (0.26 g) of the triazine **20b** as a yellow powder. M.p. > 230 °C; ^{1}H NMR ($CDCl_3$): $\delta = 8.67$ (dd, $^3J = 6.8$, $^4J = 1.6$ Hz, 2H), 8.23 (m, 4H, H_3), 8.14 ppm (s, 2H, NH_2); ^{13}C NMR ($CDCl_3$): $\delta = 170.2$ (2Cq), 167.9 (NH_2-CqTz), 166.0 (2CO), 153.6 (2Cq), 148.7 (2Cq), 138.6 ($2C_3$ or $2C_4$), 126.9 ($2C_5$), 126.7 ppm ($2C_3$ or $2C_4$); HRMS (MALDI): *m/z* calcd for $C_{15}H_{10}N_6O_4Na$: 361.0656 $[M+Na]^+$; found: 361.0653.

General procedure D: Peptide coupling route to amides

HOBt (0.3 equiv per acid functional group), the corresponding amine (3 equiv per acid functional group), and EDC (1.05 equiv per acid functional group) were successively added to a solution of carboxylic acid in DMF (0.05 M). After 48 h at RT, DMF was evaporated and dichloromethane was added. The solution was washed 3 times with water, dried (Na_2SO_4) and evaporated under reduced pressure. The expected amide was purified by flash chromatography on silica gel.

6,6′-(2-Amino-1,3,5-triazin-4,6-diyl)-2,2′-di(*N*,*N*-diethyl)picolinamide (2a): Compound **2a** was obtained by the general procedure

D with acid **20** (500 mg, 1.5 mmol, 1.0 equiv), EDC (609 mg, 3.1 mmol, 2.1 equiv), HOBt (139 mg, 0.9 mmol, 0.6 equiv), *N*,*N*-diethylamine (458 μL, 4.4 mmol, 6.0 equiv) in dry DMF (40 mL). The crude product was purified by chromatography on silica gel (eluent: AcOEt/MeOH 95:5). The expected product **2a** was obtained pure with 59% yield (392 mg). M.p. 196 °C; ^{1}H NMR ($CDCl_3$): $\delta = 8.65$ (dd, $^3J = 7.6$, $^4J = 0.8$ Hz, 2H, H_3), 7.97 (t, $^3J = 7.6$ Hz, 2H, H_4), 7.76 (dd, $^3J = 7.6$, $^4J = 0.8$ Hz, 2H, H_5), 7.35 (m, 2H, NH_2), 3.62 (q, $^3J = 7.2$ Hz, 4H, $2CH_2$), 3.46 (q, $^3J = 7.2$ Hz, 4H, $2CH_2$), 1.33 (t, $^3J = 7.2$ Hz, 6H, $2CH_3$), 1.30 ppm (t, $^3J = 7.2$ Hz, 6H, $2CH_3$); ^{13}C NMR ($CDCl_3$): $\delta =$ 170.9 (2Cq), 168.2 (2CO and NH_2-CqTz), 154.9 (2Cq), 152.8 (2Cq), 137.6 ($2C_4$), 125.1 ($2C_3$), 124.9 ($2C_5$), 43.6 ($2CH_2$), 40.5 ($2CH_2$), 14.4 ($2CH_3$), 12.9 ppm ($2CH_3$); HRMS (EI): *m/z* calcd for $C_{23}H_{28}N_8O_2$: 448.2335 $[M]^+$; found: 448.2336.

6,6′-(2-Amino-1,3,5-triazin-4,6-diyl)-2,2′-di(*N*-ethyl-*N*-phenyl)picolinamide (2b): Compound **2b** was obtained by the General Procedure **D** with acid **20b** (350 mg, 1.0 mmol, 1.0 equiv), EDC (425 mg, 2.2 mmol, 2.1 equiv), HOBt (100 mg, 0.6 mmol, 0.6 equiv), *N*-ethylaniline (389 μL, 3.1 mmol, 6.0 equiv) in dry DMF (30 mL). The crude product was purified by chromatography on silica gel (eluent: AcOEt/MeOH 95:5). The expected product **2b** was obtained with 54% yield (248 mg) as a white powder. M.p. > 230 °C; ^{1}H NMR ($CDCl_3$): $\delta = 8.44$ (b, 2H, H_5), 8.11 (b, 2H, NH_2), 7.70 (b, 2H, H_4), 7.43 (b, 2H, H_3), 7.17 (b, 8H, H_{Phenyl}), 7.09 (b, 2H, H_{Phenyl}), 4.09 (q, $^3J = 7.2$ Hz, 4H, $2CH_2$), 1.30 (t, $^3J = 7.2$, 6H, $2CH_3$); ^{13}C NMR ($CDCl_3$): $\delta =$ 170.5 (2Cq), 168.2 (NH_2-Cq), 168.1 (2CO), 154.2 (2Cq), 153.2 (2Cq), 142.5 (2Cq), 136.6 ($2C_4$), 129.0 ($4C_{Phenyl}$), 128.1 ($4C_{Phenyl}$), 126.9 ($2C_{Phenyl}$), 125.6 ($2C_3$), 124.7 ($2C_5$), 45.2 ($2CH_2$), 12.9 ppm ($2CH_3$); HRMS (ESI$^+$): *m/z* calcd for $C_{31}H_{28}N_8O_2Na$: 567.2233 $[M+Na]^+$; found: 567.2232.

6,6′-(2-Amino-1,3,5-triazin-4,6-diyl)-2,2′-di(*N*,*N*-dioctyl)picolinamide (2c): Compound **2c** was obtained by the General Procedure **D** with acid **20b** (500 mg, 1.5 mmol, 1.0 equiv), EDC (608 mg, 2.2 mmol, 2.1 equiv), HOBt (139 mg, 0.6 mmol, 0.6 equiv), and *N*,*N*-dioctylamine (1.34 mL, 3.1 mmol, 6.0 equiv) in dry DMF (16 mL). The crude product was purified by chromatography on silica gel (eluent: PE/AcOEt 60:40). The expected product **2c** was obtained pure with 10% yield (118 mg) as a yellow oil. ^{1}H NMR ($CDCl_3$): $\delta =$ 8.67 (dd, $^3J = 7.8$, $^4J = 0.9$ Hz, 2H), 7.96 (t, $^3J = 7.8$ Hz, 2H), 7.75 (dd, $^3J = 7.8$, $^4J = 0.9$ Hz, 2H), 6.95 (b, 2H, NH_2), 3.52 (m, 4H, $2CH_2$), 3.41 (m, 4H, $2CH_2$), 1.71 (m, 8H, $4CH_2$), 1.31 (m, 20H, $10CH_2$), 1.09 (m, 20H, $10CH_2$), 0.87 (t, $^3J = 6.9$ Hz, 6H, $2CH_3$), 0.77 ppm (t, $^3J = 6.9$ Hz, 6H, $2CH_3$); ^{13}C NMR ($CDCl_3$): $\delta = 170.9$ (2Cq), 168.4 (2CO), 168.2 (NH_2-CqTz), 155.2 (2Cq), 152.7 (2Cq), 137.6 ($2C_4$), 125.3 ($2C_3$), 124.9 ($2C_5$), 49.2 ($2CH_2$), 46.4 ($2CH_2$), 31.8 ($2CH_2$), 31.7 ($2CH_2$), 29.7 ($2CH_2$), 29.4 ($2CH_2$), 29.3 ($2CH_2$), 29.1 ($2CH_2$), 28.9 ($2CH_2$), 27.6 ($2CH_2$), 27.3 ($2CH_2$), 26.8 ($2CH_2$), 22.6 ($2CH_2$), 22.5 ($2CH_2$), 14.1 ($2CH_3$), 14.0 ppm ($2CH_3$); HRMS (MALDI): *m/z* calcd for $C_{47}H_{76}N_8O_2Na$: 807.5983 $[M+Na]^+$; found: 807.5960.

General procedure E: Acid chloride route to amides

Carboxylic acid was dissolved in $SOCl_2$ and the mixture was heated at 90 °C for 2 h. $SOCl_2$ was eliminated by evaporation and the obtained acid chloride was dissolved in freshly distilled dichloromethane. After cooling at 0 °C, triethylamine (1.5 equiv per acid functional group) and the corresponding amine (3 equiv per acid functional group) were successively added and the mixture was stirred at RT until total consumption of the corresponding acid chloride as monitored by TLC. The mixture was diluted in dichloromethane, washed with water, dried (Na_2SO_4), filtered and evaporated under reduced pressure. The expected amide was purified by flash chromatography on silica gel.

6,6′-(1,10-Phenanthrolin-2,9-diyl)-2,2′-di(*N*,*N*-diethyl)picolinamide (1a): Compound **1a** was obtained by the General Procedure **E** with acid **13** (298 mg, 0.7 mmol, 1.0 equiv), $SOCl_2$ (6.0 mL), CH_2Cl_2 (8.0 mL), Et_3N (594 μL, 4.26 mmol, 6.0 equiv), and *N*,*N*-dietylamine (220 μL, 2.1 mmol, 3.0 equiv). The crude product was purified by chromatography on silica gel (eluent: PE/AcOEt, 20:80). The expected product **1a** was obtained pure with 52% yield (210 mg) as a whitish powder. M.p. 201 °C; ^{1}H NMR ($CDCl_3$): $\delta = 9.11$ (dd, $^3J = 7.8$, $^4J = 0.6$ Hz, 2H, $H_{3'}$), 8.88 (d, $^3J = 8.4$ Hz, 2H, H_3), 8.42 (d, $^3J = 8.4$ Hz, 2H, H_4), 8.10 (t, $^3J = 7.8$ Hz, 2H, $H_{4'}$), 7.89 (s, 2H, H_5), 7.72 (dd, $^3J = 7.8$, $^4J = 0.6$ Hz, 2H, $H_{5'}$), 3.65 (q, $^3J = 6.9$ Hz, 4H, $2CH_2$), 3.47 (q, $^3J = 6.9$ Hz, 4H, $2CH_2$),1.34 (t, $^3J = 6.9$ Hz, 6H, $2CH_3$), 1.27 ppm (t, $^3J = 6.9$ Hz, 6H, $2CH_3$); ^{13}C NMR ($CDCl_3$): $\delta = 168.2$ (2CO), 155.1 (2Cq), 154.2 (2Cq), 154.1 (2Cq), 145.0 (2Cq), 137.6 ($2C_{4'}$), 136.9 ($2C_4$), 128.8 (2Cq), 126.5 ($2C_5$), 123.3 ($2C_{5'}$), 122.2 ($2C_{3'}$), 120.5 ($2C_3$), 42.9 ($2CH_2$), 39.9 ($2CH_2$), 14.1 ($2CH_3$), 12.5 ppm ($2CH_3$); HRMS (EI): *m/z* calcd for $C_{32}H_{32}N_6O_2$ 532.2587 $[M]^+$; found: 532.2587.

6,6′-(1,10-Phenanthrolin-2,9-diyl)-2,2′-di(*N*-ethyl-*N*-phenyl)picolinamide (1b): Compound **1b** was obtained by the General Procedure **E** with acid **13** (500 mg, 1.2 mmol, 1.0 equiv), $SOCl_2$ (10.0 mL), CH_2Cl_2 (12.0 mL), Et_3N (991 μL, 7.1 mmol, 6.0 equiv), and *N*-ethylaniline (447 μL, 3.5 mmol, 3.0 equiv). The crude product was purified by chromatography on silica gel (eluent: PE/AcOEt 40:60). The expected product **1b** was obtained pure in 31% yield (230 mg) as a whitish powder. M.p. > 230 °C; ^{1}H NMR ($CDCl_3$): $\delta = 8.90$ (d, $^3J = 7.8$ Hz, 2H, $H_{3'}$), 8.35 (m, 4H, H_3, H_4), 7.95 (t, $^3J = 7.8$ Hz, 2H, $H_{4'}$), 7.86 (s, 2H, H_5), 7.77 (d, $^3J = 7.8$ Hz, 2H, $H_{5'}$), 7.16 (m, 8H, H_{Phenyl}), 7.03 (m, 2H, H_{Phenyl}), 4.11 (q, $^3J = 7.2$ Hz, 4H, CH_2), 1.31 ppm (t, $^3J = 7.2$ Hz, 6H, CH_3); ^{13}C NMR ($CDCl_3$): $\delta = 167.8$ (2CO), 155.2 (2Cq), 154.2 (2Cq), 153.1 (2Cq), 145.2 (2Cq), 143.4 (2Cq), 137.4 ($2C_{4'}$), 136.6 ($2C_3$ or 2 C_4), 129.0 (2Cq), 128.8 ($4C_{Phenyl}$), 127.7 ($4C_{Phenyl}$), 126.6 ($2C_5$), 126.5 ($2C_{Phenyl}$), 124.6 ($2C_{5'}$), 122.3 ($2C_{3'}$), 120.8 ($2C_3$ or $2C_4$), 45.5 ($2CH_2$), 12.8 ppm ($2CH_3$); HRMS (EI): *m/z* calcd for $C_{40}H_{32}N_6O_2$ 628.2587 $[M]^+$; found: 628.2587.

6,6′-(1,10-Phenanthrolin-2,9-diyl)-2,2′-di(*N*,*N*-dioctyl)picolinamide (1c): Compound **1c** was obtained by the General Procedure **E** with acid **13** (395 mg, 0.9 mmol, 1.0 equiv), $SOCl_2$ (8.0 mL), CH_2Cl_2 (10.0 mL), Et_3N (784 μL, 5.6 mmol, 6.0 equiv), and *N*,*N*-dioctylamine (1.06 mL, 2.8 mmol, 3.0 equiv). The crude product was purified by chromatography on silica gel (eluent: PE/AcOEt 40:60). The expected product **1c** was obtained pure with 58% yield (475 mg) as a yellow oil. ^{1}H NMR ($CDCl_3$): $\delta = 9.12$ (d, $^3J = 7.8$ Hz, 2H), 8.84 (d, $^3J = 8.4$ Hz, 2H), 8.38 (d, $^3J = 8.4$ Hz, 2H), 8.08 (t, $^3J = 7.8$ Hz, 2H), 7.87 (s, 2H), 7.69 (d, $^3J = 7.8$ Hz, 2H), 3.56 (q, $^3J = 7.8$ Hz, 4H, $2CH_2$), 3.38 (q, $^3J = 7.8$ Hz, 4H, $2CH_2$), 1.73 (m, 8H, $4CH_2$), 1.37 (m, 20H, $10CH_2$), 1.27 (m, 20H, $10CH_2$), 1.09 (t, $^3J = 6.9$, 6H, $2CH_3$), 0.74 ppm (t, $^3J = 6.9$, 6H, $2CH_3$); ^{13}C NMR ($CDCl_3$): $\delta = 168.8$ (2CO), 155.6 (2Cq), 154.7 (2Cq), 154.6 (2Cq), 145.6 (2Cq), 137.9 ($2C_{4'}$), 137.0 ($2C_4$), 129.2 (2Cq), 126.8 ($2C_5$), 123.7 ($2C_{5'}$), 122.4 ($2C_{3'}$), 120.8 ($2C_3$), 49.1 ($2CH_2$), 46.0 ($2CH_2$), 31.8 ($2CH_2$), 31.6 ($2CH_2$), 29.4 ($2CH_2$), 29.3 ($2CH_2$), 29.2 ($4CH_2$), 29.1 ($2CH_2$), 27.6 ($2CH_2$), 27.1 ($2CH_2$), 26.7 ($2CH_2$), 22.6 ($2CH_2$), 22.5 ($2CH_2$), 14.1 ($2CH_3$), 13.9 ppm ($2CH_3$); HRMS (MALDI): *m/z* calcd for $C_{56}H_{80}N_6O_2Na$: 891.6235 $[M+Na]^+$; found: 891.6237.

6,6′-(1,10-Phenanthrolin-2,9-diyl)-2,2′-di(*N*-hexyl-*N*-phenyl)picolinamide (1d): Compound **1d** was obtained by the General Procedure **E** with acid **13** (500 mg, 1.2 mmol, 1.0 equiv), $SOCl_2$ (10.0 mL), CH_2Cl_2 (12.0 mL), Et_3N (719 mg, 7.1 mmol, 6.0 equiv), and *N*-hexylaniline (642 mg, 3.5 mmol, 3.0 equiv). The crude product was purified by chromatography on silica gel (eluent: CH_2Cl_2/MeOH 98:2). The expected product **1d** was obtained pure with 58% yield (508 mg) as a whitish powder. M.p. 168 °C; ^{1}H NMR ($CDCl_3$): $\delta =$ 8.85 (d, $^3J = 7.2$ ppm, 2H), 8.20 (m, 4H, H_3), 7.91 (m, 2H), 7.79 (s, 2H), 7.75 (d, $^3J = 7.2$ ppm, 2H), 7.15 (m, 8H, H_{Phenyl}), 7.01 (m, 2H,

H_{Phenyl}), 4.01 (m, 4H, $2CH_2$), 1.70 (m, 4H, $2CH_2$), 1.31 (m, 12H, $6CH_2$), 0.88 ppm (m, 6H, $2CH_3$); ^{13}C NMR ($CDCl_3$): $\delta = 168.0$ (2CO), 155.1 (2Cq), 154.0 (2Cq), 153.2 (2Cq), 145.1 (2Cq), 143.6 (2Cq), 137.4 ($2C_{4'}$), 136.7 ($2C_3$ or $2C_4$), 129.0 (2Cq), 128.7 ($4C_{Phenyl}$), 127.6 ($4C_{Phenyl}$), 126.6 ($2C_5$), 126.4 ($2C_{Phenyl}$), 124.6 ($2C_{5'}$), 122.2 ($2C_{3'}$), 120.8 ($2C_3$ or $2C_4$), 50.5 ($2CH_2$), 31.5 ($2CH_2$), 27.5 ($2CH_2$), 26.6 ($2CH_2$), 22.5 ($2CH_2$), 14.0 ppm ($2CH_3$); HRMS (MALDI): *m/z* calcd for $C_{48}H_{48}N_6O_2Na$: 763.3731 $[M+Na]^+$; found: 763.3727.

6,6′-(2-Phenyl-1,3,5-triazin-4,6-diyl)-2,2′-di(*N*,*N*-diethyl)picolinamide (3a): Compound **3a** was obtained by the General Procedure **E** with acid **20a** (540 mg, 1.4 mmol, 1.0 equiv), $SOCl_2$ (15.0 mL), CH_2Cl_2 (17.0 mL), Et_3N (1.14 mL, 8.2 mmol, 6.0 equiv) and diethylamine (423 μL, 4.1 mmol, 3.0 equiv). The crude product was purified by chromatography on silica gel (eluent: PE/AcOEt 30:70). The expected product **3a** was obtained pure with 44% yield (308 mg) as a white powder. M.p. 194 °C; ^1H NMR ($CDCl_3$): $\delta = 8.80$ (m, 4H, H_3, $H_{2'}$), 8.05 (t, $^3J = 7.8$ Hz, 2H, H_4), 7.96 (dd, $^3J = 7.8$ Hz, $^4J = 0.8$ Hz, 2H, H_5), 7.61 (m, 3H, $H_{3'}$, $H_{4'}$), 3.62 (q, $^3J = 7.2$ Hz, 8H, $4CH_2$), 1.33 (t, $^3J = 7.2$ Hz, 6H, $2CH_3$), 1.49 ppm (t, $^3J = 7.2$ Hz, 6H, $2CH_3$); ^{13}C NMR ($CDCl_3$): $\delta = 173.1$ (Ph-CqTz), 171.4 (2Cq), 167.7 (2CO), 155.3 (2Cq), 152.0 (2Cq), 137.9 ($2C_4$), 135.6 (Cq-Ph), 133.0 ($C_{4'}$), 129.3 ($2C_{2'}$), 128.7 ($2C_{3'}$), 126.6 ($2C_5$), 125.4 ($2C_3$), 43.8 ($2CH_2$), 41.0 ($2CH_2$), 14.7 ($2CH_3$), 12.9 ppm ($2CH_3$); HRMS (EI): *m/z* calcd for $C_{29}H_{31}N_7O_2$: 509.2539 $[M]^+$; found: 509.2536.

6,6′-(2-Phenyl-1,3,5-triazin-4,6-diyl)-2,2′-di(*N*-ethyl-*N*-phenyl)picolinamide (3b): Compound **3b** was obtained by the General Procedure **E** with acid **20a** (500 mg, 1.2 mmol, 1.0 equiv), $SOCl_2$ (14.0 mL), CH_2Cl_2 (16.0 mL), Et_3N (1.05 mL, 7.5 mmol, 6.0 equiv), and *N*-ethylaniline (482 μL, 3.7 mmol, 3.0 equiv). The crude product was purified by chromatography on silica gel (eluent: PE/AcOEt, 20:80). The expected product **3b** was obtained pure with 59% yield (450 mg) as a white powder. M.p. 204 °C; ^1H NMR ($CDCl_3$): $\delta = 8.75$ (d, $^3J = 7.2$ Hz, 2H, $H_{2'}$), 8.58 (b, 2H, H_3), 7.89 (b, 2H, H_4), 7.80 (b, 2H, H_5), 7.64 (m, 3H, $H_{3'}$, $H_{4'}$), 7.17 (b, 8H, H_{Phenyl}), 6.99 (b, 2H, H_{Phenyl}), 4.08 (q, $^3J = 7.2$ Hz, 4H, $2CH_2$), 1.30 ppm (b, 6H, $2CH_3$); ^{13}C NMR ($CDCl_3$): $\delta = 172.8$ (Ph-CqTz), 170.7 (2Cq), 167.8 (2CO), 154.9 (2Cq), 152.0 (2Cq), 142.7 (2Cq), 137.2 ($2C_4$), 135.5 (Cq-Ph), 133.0 ($C_{4'}$), 129.4 ($2C_{2'}$), 128.8 ($4C_{Phenyl}$), 128.5 ($4C_{Phenyl}$), 128.1 ($2C_{3'}$), 126.7 ($2C_{Phenyl}$), 126.5 ($2C_5$), 125.0 ($2C_3$), 45.2 ($2CH_2$), 12.8 ppm ($2CH_3$); HRMS (EI): *m/z* calcd for $C_{37}H_{31}N_7O_2$ 605.2539 $[M]^+$; found: 605.2539.

6,6′-(2-Phenyl-1,3,5-triazin-4,6-diyl)-2,2′-di(*N*,*N*-dioctyl)picolinamide (3c): Compound **3c** was obtained by the General Procedure **E** with acid **20a** (200 mg, 0.5 mmol, 1.0 equiv), $SOCl_2$ (6.0 mL), CH_2Cl_2 (10.0 mL), Et_3N (418 μL, 3.0 mmol, 6.0 equiv), and *N*,*N*-dioctylamine (452 μL, 1.5 mmol, 3.0 equiv). The crude product was purified by chromatography on silica gel (eluent: PE/AcOEt 30:70). The expected product **3c** was obtained pure with 56% yield (236 mg) as a yellow oil. ^1H NMR ($CDCl_3$): $\delta = 8.80$ (m, 4H, H_3 and $H_{2'}$), 8.03 (t, $^3J = 7.8$ Hz, 2H, H_4), 7.92 (dd, $^3J = 7.8$, $^4J = 0.9$ Hz, 2H, H_5), 7.60 (m, 3H, $H_{3'}$, $H_{4'}$), 3.60 (m, 8H, $4CH_2$), 1.78 (m, 8H, $4CH_2$), 1.32 (m, 20H, $10CH_2$), 1.06 (m, 20H, $10CH_2$), 0.88 (t, $^3J = 6.9$ Hz, 6H, $2CH_3$), 0.72 ppm (t, $^3J = 6.9$ Hz, 6H, $2CH_3$); ^{13}C NMR ($CDCl_3$): $\delta = 173.1$ (Ph-CqTz), 171.2 (2Cq), 167.8 (2CO), 155.5 (2Cq), 151.8 (2Cq), 137.9 ($2C_4$), 135.5 (Cq-Ph), 133.1 ($C_{4'}$), 129.4 ($2C_{2'}$), 128.7 ($2C_{3'}$), 126.6 ($2C_5$), 125.3 ($2C_3$), 49.3 ($2CH_2$), 46.8 ($2CH_2$), 31.8 ($2CH_2$), 31.6 ($2CH_2$), 29.5 ($2CH_2$), 29.3 ($2CH_2$), 29.1 ($4CH_2$), 29.0 ($2CH_2$), 27.6 ($2CH_2$), 27.3 ($2CH_2$), 26.8 ($2CH_2$), 22.6 ($2CH_2$), 22.4 ($2CH_2$), 14.1 ($2CH_3$), 14.0 ppm ($2CH_3$); HRMS (MALDI): *m/z* calcd for $C_{53}H_{79}N_7NaO_2$: 868.6187 $[M+Na]^+$; found: 868.6195.

6,6′-(2-Trifluoromethyl-1,3,5-triazin-4,6-diyl)-2,2′-di(*N*,*N*-diethyl)-picolinamide (4a): Compound **4a** was obtained by the General Procedure **E** with acid **20d** (400 mg, 1.0 mmol, 1.0 equiv), $SOCl_2$ (11.0 mL), CH_2Cl_2 (15.0 mL), Et_3N (853 μL, 6.1 mmol, 6.0 equiv), and diethylamine (317 μL, 3.1 mmol, 3.0 equiv). The crude product was purified by chromatography on silica gel (eluent: PE/AcOEt 30:70). The expected product **4a** was obtained with 58% yield (290 mg) as a whitish powder. M.p. 165 °C; ^1H NMR ($CDCl_3$): $\delta = 8.78$ (dd, $^3J = 7.8$, $^4J = 1.8$ Hz, 2H, H_3), 8.04 (m, 4H, H_4, H_5), 3.57 (m, 8H, $4CH_2$), 1.46 (t, $^3J = 7.2$ Hz, 6H, $2CH_3$), 1.31 ppm (t, $^3J = 7.2$ Hz, 6H, $2CH_3$); ^{13}C NMR ($CDCl_3$): $\delta = 172.7$ (2Cq), 167.1 (2CO), 166.3 (q, $^{CF}J = 38.4$ Hz, CF_3-CqTz), 155.5 (2Cq), 149.9 (2Cq), 138.2 ($2C_4$), 127.8 ($2C_5$), 126.0 ($2C_3$), 118.9 (q, $^{CF}J = 276.5$ Hz, CF_3), 44.0 ($2CH_2$), 41.1 ($2CH_2$), 14.3 ($2CH_3$), 12.7 ppm ($2CH_3$); ^{19}F NMR ($CDCl_3$): $\delta = -72.04$ ppm (s, CF_3); HRMS (MALDI): *m/z* calcd for $C_{24}H_{27}F_3N_7O_2$: 502.2173 $[M+H]^+$; found: 502.2175.

6,6′-(2-Trifluoromethyl-1,3,5-triazin-4,6-diyl)-2,2′-di(N-ethyl-*N*-phenyl)picolinamide (4b): Compound **4b** was obtained by the General Procedure **E** with acid **20d** (500 mg, 1.0 mmol, 1.0 equiv), $SOCl_2$ (14.0 mL), CH_2Cl_2 (20.0 mL), Et_3N (1.07 mL, 7.7 mmol, 6.0 equiv), and *N*-ethylaniline (492 μL, 3.8 mmol, 3.0 equiv). The crude product was purified by chromatography on silica gel (eluent: PE/AcOEt 50:50). The expected product **4b** was obtained with 71% yield (540 mg) as a whitish powder. M.p. 178 °C; ^1H NMR ($CDCl_3$): $\delta = 8.54$ (b, 2H, H_3), 7.89 (b, 4H, H_1, H_2), 7.16 (b, 8H, H_4, H_5), 6.98 (m, 2H, H_6), 4.05 (q, $^3J = 6.9$ Hz, 4H, $2CH_2$), 1.29 ppm (t, $^3J = 6.9$ Hz, 6H, $2CH_3$); ^{13}C NMR ($CDCl_3$): $\delta = 172.0$ (2Cq), 167.2 (2CO), 165.8 (q, $^{CF}J = 38.6$ Hz, CF_3-CqTz), 155.1 (2Cq), 149.9 (2Cq), 142.5 (2Cq), 137.6 ($2C_2$), 129.2 ($4C_4$ or $4C_5$), 128.7 ($4C_4$ or $4C_5$), 128.2 ($2C_1$), 127.4 ($2C_6$), 126.7 ($2H_3$), 119.1 (q, $^{CF}J = 264.8$ Hz, CF_3), 45.3 ($2CH_2$), 12.7 ppm ($2CH_3$); ^{19}F NMR ($CDCl_3$): $\delta = -71.69$ ppm (s, CF_3); HRMS (MALDI): *m/z* calcd for $C_{32}H_{26}F_3N_7O_2Na$: 620.1992 $[M+Na]^+$; found: 620.1995.

Solvent-extraction tests

Chemical and solutions: *n*-Octanol was purchased from Aldrich. Depleted uranyl nitrate from Prolabo, purity 99.9%, was used without further purification. $^{239-240}Pu^{IV}$ solution was purified by fixation on a DOWEX anion exchange resin at 7 M HNO_3 and elution with 0.5 M HNO_3. $^{237}Np^{V}$ stock solution was prepared from a $^{237}Np^{V-VI}$ mixture solution by treating with $NaNO_2$. NpV was then precipitated by the addition of sodium hydroxide. The NpO_2OH, xH_2O green solid was then washed with water, dried and dissolved in 1 M HCl. $^{241}Am^{III}$ stock solution was obtained by dissolution of AmO_2 in HNO_3 followed by Am^{III} purification on a DOWEX-50 cation exchange resin. Am^{3+} in 0.1 M HNO_3 was sorbed on the resin, washed several times with 0.1 M HNO_3 and eluted with 5 M HNO_3. Americium hydroxide was then precipitated by adding sodium hydroxide, washed and redissolved in 1 M HNO_3. $^{244}Cm^{III}$ stock solution was obtained from the raffinate of the Am/Cm separation process performed in Atalante facility in 2002.[27] ^{152}Eu was purchased from CERCA-LEA and used without further purification. All these radioactive solutions were manipulated in gloveboxes.

General procedures: Aqueous solutions of nitric acid ($[HNO_3] = 3$ M), spiked with radionuclides were contacted for 60 min by means of an automatic vortex shaker with organic solutions ($V_{aq} = V_{org}$), containing the ligand diluted in *n*-octanol. Aqueous and organic solutions were mixed in Nalgene tubes thermostated at 25 °C. After the phase separation by centrifugation and dilution, 500 μL samples of both diluted phases were analyzed using a gamma-counting spectrometer (HPGe detector, CANBERRA) to measure activities of ^{241}Am and ^{152}Eu. Activities of $^{239+240}Pu$, ^{237}Np, ^{241}Am, and ^{244}Cm were measured using an alpha counting spectrometer (silicon detector, CANBERRA). Samples for alpha analysis were prepared by calcinations of 10 μL of the solution on a stain-

less steel disk and carried out in triplicate to reduce uncertainties in these measurements. $^{238}U^{VI}$ concentration was analyzed by X-ray fluorescence (METOREX International) in aqueous phases only, using ^{241}Am as a source for X-rays. For all samples, the analysis was repeated three times. The concentration of nitric acid in the aqueous phase at equilibrium ($[HNO_3]_{eq}$) was determined by automatic titration with NaOH 0.1 M. The distribution ratio D_M for a metallic cation M is defined as the ratio of the concentration of the metallic species in the organic phase at equilibrium over its concentration in the aqueous phase at equilibrium. The separation factor $SF_{M1/M2}$ for two metallic cations M1 and M2 is defined as the ratio of their distribution ratios.

Extraction of $^{239+240}Pu^{IV}$, ^{241}Am, ^{244}Cm and ^{152}Eu: An aqueous stock solution was spiked with trace amounts of $^{239+240}Pu^{IV}$, ^{241}Am, ^{244}Cm and ^{152}Eu ($[cations] < 10^{-4}$ mol L^{-1}). The aqueous and the organic solution (750 μL) were contacted and were then analyzed without dilution.

Extraction of $^{238}U^{VI}$: The uranium stock solution was prepared by dissolution of uranium nitrate in nitric acid ($[UO_2^{2+}] = 4.5.10^{-3}$ mol L^{-1}). The aqueous and the organic solutions ($[L] = 0.01$ mol L^{-1}) were contacted (950 μL). The aqueous phase was diluted 10 times in HNO_3 1 M and the organic phase 10 times in a suitable organic media before analysis. HRMS (MALDI): *m/z* calcd for $C_{32}H_{26}F_3N_7O_2Na$: 620.1992; found: 620.199.

Extraction of $^{237}Np^{V-VI}$: ^{237}Np stock solution was prepared from an 0.1 mol L^{-1} in 1 M HCl stock solution by a 170 times dilution in HNO_3 3 M ($[Np] = 5.8.10^{-4}$ mol L^{-1}). The aqueous and the organic solutions (300 μL; $[L] = 0.01$ mol L^{-1}) were contacted and then analyzed by alpha spectrometry without further dilution.

Keywords: actinides · lanthanides · ligands · heterocycles · synthetic methods

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