[10] The intensity of the absorbance at 249 nm is proportional to the number of Pt^{II} ions in the dendrimer over the range 0–60. Titration results also show by plots of the absorbance at 225 or 300 nm against the number of Pd^{II} in the dendrimer that G4-OH can sorb at least 40 Pd^{II} ions.

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[12] Specimens for HRTEM observations were prepared by placing a drop of an aqueous solution of 0.05 mM G4-OH(Pt_n or Pd_n) on a holey-carbon-coated grid. We recorded the TEM images digitally with a charge-coupled-device (CCD) camera.

[13] The shifts of the $Pt(4f_{7/2})$ peak from 72.8 to 71.3 eV and the $Pt(4f_{5/2})$ peak from 75.7 to 74.4 eV in the XPS spectra indicate the reduction of the Pt^{II} ion inside dendrimer. For the dendrimer-Pd composite G4-OH$(Pd^{2+})_{40}$ we observed the $Pd(3d_{5/2})$ peak shifted from 337.6 to 334.9 eV upon reduction. However, two oxidation states (II and 0) of Pd prior to reduction were observed. The zero state Pd may arise from the X-ray-induced reduction of Pd^{2+} centers.

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Efficient, Reversible Redox-Switching of Molecular First Hyperpolarizabilities in Ruthenium(II) Complexes Possessing Large Quadratic Optical Nonlinearities**

Benjamin J. Coe,* Stephan Houbrechts,
Inge Asselberghs, and André Persoons

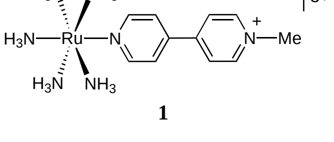
Two research areas attracting great interest within the emerging field of "molecular electronics/photonics" are nonlinear optical (NLO) materials[1] and molecular switches.[2] It is anticipated that the former will be exploited in optoelectronic technologies, whilst the latter will provide the basis for a range of molecular-scale devices. The fusion of these two themes, that is the development of materials exhibiting switchable NLO properties, can hence be expected to lead to exciting and novel applications. However, this has been attempted in only a few instances to date, and with limited success.[3–6]

At the molecular level, quadratic NLO effects are governed by first hyperpolarizabilities, β, which can lead to macroscopic phenomena such as second harmonic generation (SHG). Photoswitching of SHG has been observed recently in solutions of bacteriorhodopsin[3] and in crystals of *N*-salicylidene-4-bromoaniline.[4] In other studies focusing on molecular properties, a bis(thienyl)ethene was found to exhibit a change in β on photoisomerization,[5] and it has been suggested that photoinduced proton-transfer may alter β in nitrobenzyl pyridines.[7]

Transition metal organometallic and coordination complexes are an important class of NLO molecules,[1d, 8] for which β data is becoming increasingly available,[8, 9] largely due to the introduction of the versatile hyper-Rayleigh scattering (HRS) technique.[10] The presence of redox-active metal centers provides extensive opportunities for modulation of NLO responses, but this has only been addressed previously in SHG photoswitching from $[Ru^{II}(bpy)_3]^{2+}$ (bpy = 2,2′-bipyridine) derivatives in Langmuir–Blodgett (L–B) films.[6] In the latter study, a 30% decrease in SHG intensity was ascribed to the change in β upon metal-to-ligand charge-transfer (MLCT) excitation. However, although it has been reported that such octupolar complexes exhibit extremely large β values,[9b] it now appears that these claims were exaggerated.[11] Furthermore, only modest β changes occur upon oxidation of $[Ru^{II}(bpy)_3]^{2+}$.[12]

We have recently discovered that ruthenium(II) ammine complexes of 4,4′-bipyridinium ligands exhibit large, tunable β values which are associated with intense, low-energy MLCT excitations.[13] The electron-rich, d^6 centers $[Ru^{II}(NH_3)_5]^{2+}$ or *trans*-$[Ru^{II}(NH_3)_4(L)]^{2+}$ (L = 4-dimethylaminopyridine or 1-methylimidazole) behave as powerful π donors in conjunction with the ligands *N*-R-4,4′-bipyridinium (R = methyl (MeQ^+), phenyl (PhQ^+), or 4-acetylphenyl (4-$AcPhQ^+$)). These complexes are ideally suited towards redox-switching of NLO responses because although air-stable, they feature completely reversible, one-electron $Ru^{III/II}$ couples at readily accessible potentials (0.46–0.48 V vs SCE for the PF_6^- salts in acetonitrile (MeCN)).[13]

We have previously reported β data for $[Ru^{II}(NH_3)_5(L)](PF_6)_3$ (L = MeQ^+ (**1**), PhQ^+ (**2**), 4-$AcPhQ^+$ (**3**))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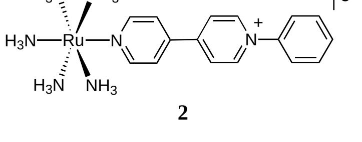
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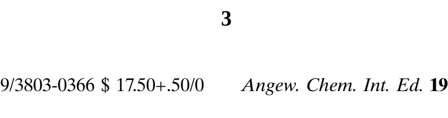
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[**] Dr Houbrechts was a Research Assistant of the Fund for Scientific Research-Flanders. This work was supported by research grants from The Royal Society, from the Belgian National Fund for Scientific Research (G.0308.96), from the Belgian government (IUAP-P4/11), and from the University of Leuven (GOA/1/95). We thank Johnson Matthey plc for a generous loan of ruthenium trichloride.

obtained from 1064 nm HRS measurements in MeCN.[13b,c] Due to absorption in the region of the second harmonic at 532 nm, the β_{1064} values are resonantly enhanced and the two-level model[14] was used to derive static hyperpolarizabilities, β_0. In order to confirm the validity of these data, we have carried out a limited solvent-dependence investigation with [**2**](PF_6)$_3$ (Table 1). As expected,[13a] the MLCT absorption maximum red shifts as the solvent Gutmann donor number increases. Decreasing absorption at 532 nm causes a reduction in β_{1064}, but β_0 remains constant within the experimental error. This proves that our β_0 values determined in MeCN are reliable and that the two-level model is valid for these complexes. Although one solvent study with *p*-nitroaniline (pNA) indicated a solvent dependence of β_0,[16] it has been shown more recently that this may not be genuine.[17] No other investigations into the solvent-dependence of β in metal complexes have been reported.

Table 1. Solvent dependence of MLCT absorption and first hyperpolarizabilities of [**2**](PF_6)$_3$.

Solvent	DN[a] [kcal mol^{-1}]	λ_{max} [MLCT] (ε) [nm] ([M^{-1}cm^{-1}])	ε_{532}[b] [M^{-1}cm^{-1}]	β_{1064}[c] [$\times 10^{30}$ esu]	β_0[c] [$\times 10^{30}$ esu]
MeCN	14.1	628 (19 300)[d]	6200	858[d]	220[d]
acetone	17.0	654 (16 600)	3700	647	206
DMF	26.6	716 (22 600)	1500	524	233
DMSO	29.8	730 (24 500)	1100	414	193

[a] Gutmann donor number (Gutmann, V. *The Donor-acceptor Approach to Molecular Interactions*, Plenum, New York, 1978). [b] Extinction at the second harmonic wavelength (532 nm). [c] Solutions of about 10^{-5} M to ensure linear concentration dependences of $I_{2\omega}/I_{\omega}^2$. All samples were passed through a 0.45 μm filter and were checked for fluorescence by using interference filters as described elsewhere.[11, 15] One-dimensional hyperpolarizability is assumed, that is $\beta_{1064} = \beta_{333}$, and a relative error of ±15% is estimated. The quoted cgs units (esu) can be converted into SI units ($C^3 m^3 J^{-2}$) by dividing by a factor of 2.693×10^{20}. [d] Ref. [13b].

In order to facilitate chemical redox studies, [**1**](PF_6)$_3$–[**3**](PF_6)$_3$ were metathesized to their chloride salts which show improved solubility in water. HRS and absorption spectral data for [**1**]Cl_3–[**3**]Cl_3 are shown in Table 2. In each case, the MLCT absorptions are blue-shifted and of reduced intensity with respect to those in MeCN [MLCT maxima: [**1**](PF_6)$_3$, 590 nm ($\varepsilon = 15800\,M^{-1}cm^{-1}$); [**3**]($PF_6$)$_3$, 654 nm ($\varepsilon = 18000\,M^{-1}cm^{-1}$)].[13c] In the absence of a suitable reference for aqueous solutions, these β_{1064} values were determined by using the electric-field-induced-SHG β_{1064} for pNA in methanol as an external reference.[16] Their absolute magnitudes are hence of questionable accuracy and should not be compared with the data obtained in nonaqueous solvents (Table 1). However, the relative ordering confirms that β_0 increases as the acceptor strength of L increases in the order $MeQ^+ < PhQ^+ <$ 4-AcPhQ$^+$.[13c]

Table 2. UV/Vis absorption and HRS data for [**1**]Cl_3–[**3**]Cl_3 in water.

Compound	λ_{max} [$\pi \rightarrow \pi^*$] (ε) [nm] ([M^{-1}cm^{-1}])	λ_{max} [MLCT] (ε) [nm] ([M^{-1}cm^{-1}])	ε_{532}[a] [M^{-1}cm^{-1}]	β_{1064}[b] [$\times 10^{30}$ esu]	β_0[b] [$\times 10^{30}$ esu]
1	266 (15000)	580 (13000)	9400	510	67
2	280 (16600)	616 (16700)	7500	629	142
3	284 (21700)	636 (16700)	5800	656	180

[a, b] See Table 1 footnotes [b] and [c], respectively, for details. β_{1064} estimated by using the electric-field-induced-SHG β_{1064} value for pNA in methanol as an external reference.[16]

Solutions of [**1**]Cl_3–[**3**]Cl_3 in water are deep blue due to their intense MLCT absorptions. Chemical oxidation using an excess of 1:1 30% aqueous H_2O_2/2 M HCl results in complete bleaching, as shown in Figure 1 for [**2**]Cl_3. The oxidized complexes are indefinitely stable in solution and quantitative recovery of their Ru^{II} forms occurs upon reduction with 62% hydrazine hydrate solution, as indicated by ε measurements. The Ru^{III} complexes exhibit no low-energy charge-transfer absorptions because they contain two opposing electron acceptors attached to a pyridyl ring (Scheme 1). In contrast to $[Ru^{II}(NH_3)_5]^{2+}$, the d^5 $[Ru^{III}(NH_3)_5]^{3+}$ moiety is a powerful electron-withdrawing group which can engage in visible ligand-to-metal charge-transfer (LMCT) excitations when coordinated to donor-substituted ligands.[18] Indeed, other workers have previously demonstrated the use of this acceptor function in mixed-valence complexes possessing relatively large β values.[9a]

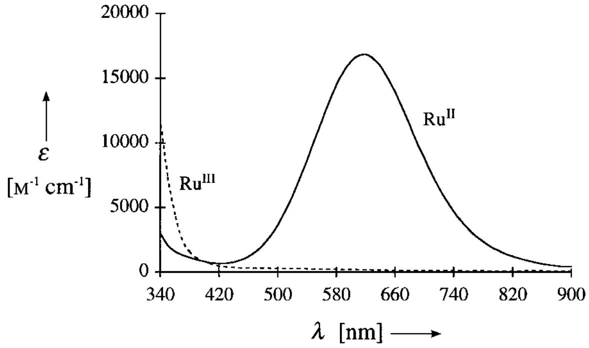
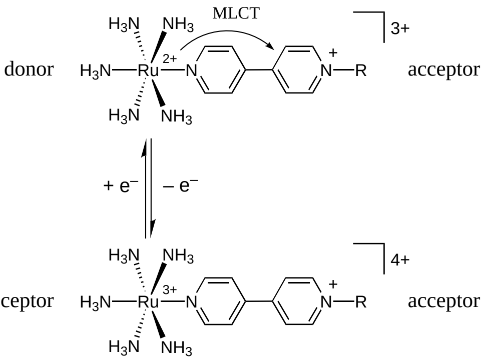


Figure 1. UV/Vis/NIR absorption spectrum of [**2**]Cl_3 (——) and of its Ru^{III} form (----) generated by H_2O_2/HCl oxidation in water (6.43×10^{-5} M).



Scheme 1. Effects of Ru-based redox in the complex cations **1**–**3** (R = Me (**1**), Ph (**2**), 4-AcPh (**3**)).

The solutions used for HRS study of [**1**]Cl_3–[**3**]Cl_3 were oxidized in situ by addition of a 1:1 mixture of 30% aqueous H_2O_2/2 M HCl. In each case, a dramatic decrease in the harmonic scattering intensity was observed, producing only very weak signals from which meaningful β values could not be derived. This is illustrated for [**3**]Cl_3 and its Ru^{III} form in Figure 2. As anticipated, the loss of the low-energy MLCT

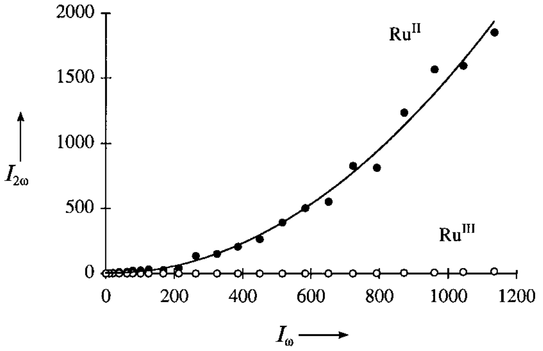


Figure 2. Plot of second harmonic intensity ($I_{2\omega}$) versus fundamental intensity (I_{ω}) for [**3**]Cl$_3$ (●) and for its Ru^{III} form (○) generated by H_2O_2/HCl oxidation in water (1.10×10^{-5} M).

absorptions results in marked attenuation of the quadratic NLO responses, corresponding to a very effective switching of β. The complete reversibility of the Ru$^{III/II}$ redox couples of these complexes shown by cyclic voltammetric studies,[13b,c] together with the reversibility of the MLCT bleaching suggests that the β switching should also be reversible. This is indeed found to be the case, as shown for **3** in Figure 3. Since $I_{2\omega}/I^2_{\omega}$ is proportional to β^2, the reduction in β on oxidation is estimated as being 10- to 20-fold, that is at least an order of magnitude.[19]

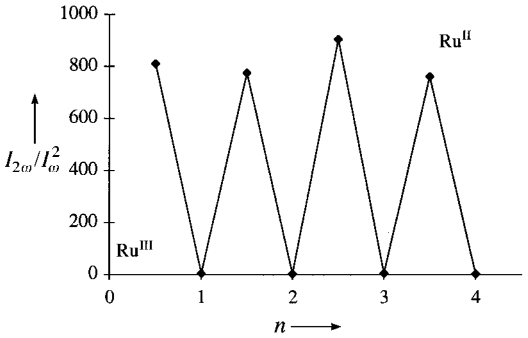


Figure 3. Redox-switching of HRS response between [**3**]Cl$_3$ and its Ru^{III} form with chemical oxidation by H_2O_2/HCl and reduction by $N_2H_4 \cdot H_2O$. All data corrected for initial concentration of 5.80×10^{-6} M; n = number of oxidations.

To conclude, we have shown that completely reversible switching of large molecular quadratic NLO responses is possible in dipolar Ru^{II}-4,4′-bipyridinium chromophores by exploitation of the redox properties of the $[Ru(NH_3)_5]^{x+}$ center ($x = 2$, 3). This constitutes a novel approach to β modulation which is considerably more effective than any demonstrated previously. These highly stable complexes are easily synthesized and will be readily modified for incorporation into L–B or other thin film materials in which redox-switching of macroscopic NLO effects will be studied.

Experimental Section

The syntheses and full characterization of the salts [**1**]$(PF_6)_3$–[**3**]$(PF_6)_3$ have been described previously.[13c] Metathesis to the chloride salts is exemplified as follows: [**1**]$(PF_6)_3$ (88 mg, 0.11 mmol) was dissolved in acetone (5 mL) and a solution of $[N(n\text{Bu})_4]Cl$ (0.5 g, 1.80 mmol) in acetone (5 mL) was added dropwise. The deep blue precipitate was filtered off, washed thoroughly with acetone, and dried under vacuum ($CaSO_4$) at ambient temperature to afford [**1**]$Cl_3 \cdot 2.5\,H_2O$ (55 mg, 98%). C, H, N analysis: [**1**]$Cl_3 \cdot 2.5\,H_2O$: Calcd for $C_{11}H_{26}Cl_3N_7Ru \cdot 2.5\,H_2O$ (%): C 25.97, H 6.14, N 19.27; found: C 26.18, H 6.24, N 19.03; [**2**]$Cl_3 \cdot 3.5\,H_2O$: Calcd for $C_{16}H_{28}Cl_3N_7Ru \cdot 3.5\,H_2O$ (%): C 32.63, H 5.99, N 16.65; found: C 32.76, H 5.59, N 16.27; [**3**]$Cl_3 \cdot 3\,H_2O$: Calcd for $C_{18}H_{30}Cl_3N_7ORu \cdot 3\,H_2O$ (%): C 34.76, H 5.83, N 15.76; found: C 34.81, H 5.76, N 15.32.

The experimental details of the HRS measurements have been described previously.[7] The general procedure for the β switching experiments with [**1**]Cl_3–[**3**]Cl_3 is exemplified as follows: To a solution of [**3**]Cl_3 in water (5.80×10^{-6} M) was added 1:1 30% aqueous H_2O_2/2 M HCl until the blue coloration was completely bleached. An excess of reagent was used in order to ensure complete oxidation and the solution was then made up to a known volume with water before HRS measurement. The complex was re-reduced by the dropwise addition of a slight excess of 62% hydrazine hydrate solution until the blue coloration was fully restored, and the solution was again diluted to a known volume with water. The quadratic coefficients were adjusted to account for the progressive dilutions following each oxidation–reduction cycle.

Received: August 26, 1998 [Z12342IE]
German version: *Angew. Chem.* **1999**, *111*, 377–380

Keywords: donor–acceptor systems · molecular switches · nonlinear optics · ruthenium

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[19] This was confirmed by the use of 100-fold concentrated solutions (ca. 10^{-3} M) which afforded larger HRS signals, allowing the derivation of β_{1064} values of 20, 35, and 62×10^{-30} esu for the oxidized forms of $[\mathbf{1}]Cl_3$, $[\mathbf{2}]Cl_3$, and $[\mathbf{3}]Cl_3$, respectively (referenced to pNA in methanol). Excessive UV absorption by H_2O_2 prevents measurement of the spectra of the Ru^{III} forms, precluding the estimation of β_0 values.

Amphiphilic *p-tert*-Butylcalix[4]arene Scaffolds Containing Exposed Carbohydrate Dendrons**

René Roy* and Jin Mi Kim

Calixarenes are cyclic molecules containing a cavity useful in host–guest chemistry.[1] Their intrinsic amphiphilic architecture also makes them ideal candidates for the study of water–monolayer surface interactions. In this respect, they surpass their cyclodextrin counterparts.[2] In spite of these interesting features—and in addition possible variation of conformational organization, substitution of the upper and lower rims, and shape and size—only limited efforts have been made to construct biologically relevant calixarenes containing carbohydrate moieties.[3, 4] In line with this concept, the synthesis of nondendritic galactose octamers attached to a calix[4]resorcarene scaffold possessing lipophilic side chains has been described. However, as opposed to our work presented herein, the hydrophilic carbohydrate residues were used for polar attachment to a polar quartz surface.[5]

We describe here the first synthesis of dendritic,[6] water-soluble, carbohydrate-containing *p-tert*-butylcalix[4]arenes and their lectin-binding properties. These carbohydrate-containing calix[4]arenes can serve as models to further investigate factors influencing multivalent carbohydrate–protein interactions at the molecular level. The lipophilic *p-tert*-butyl substituents provide the driving force for stable assembly and/or adhesion of a calixarene monolayer to a surface, while the hydrophilic carbohydrate ligands mimic the cell's saccharide-rich surface. This new type of hybrid molecules can serve as coating carbohydrate ligands in competitive solid-phase immunoassays (Figure 1).

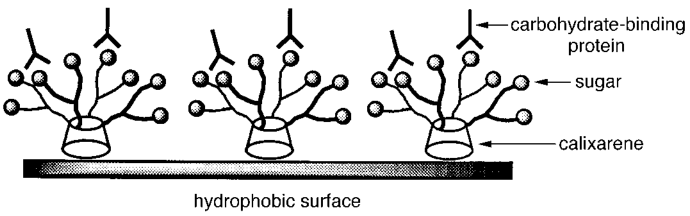

Figure 1. Glycocalix[4]arene hybrids used as coating antigens on a hydrophobic polystyrene surface.

Our model carbohydrate is the T_N antigen (GalNAcα1 →O-Ser/Thr) corresponding to one of the immunodominant epitopes found in human adenocarcinomas mucins.[7] This family of carbohydrate-associated tumor markers is usually cryptic in normal cells. We have also recently shown that the O-linked Ser/Thr residues in the analogous T antigen [Gal(β1-3)-GalNAc(α1 →O-Ser/Thr)] were not essential to generate mouse monoclonal antibodies that recognize cancer tissues.[8] Consequently, the α-linked GalNAc moieties described herein were deprived of the O-Ser/Thr aglycon.

The synthetic strategy for the construction of glycocalix[4]arenes was to attach suitable spacer-substituted α-GalNAc residues to the calix[4]arene core; both convergent and divergent approaches were employed. The key α-D-GalNAc derivative **3** was prepared in four steps from *N*-acetyl-D-galactosamine (**1**) (Scheme 1). The required calix[4]arene core **7** was prepared by transforming commercial *p-tert*-butylcalix[4]arene (**6**) into the known tetraethyl ester[9] followed by hydrolysis and treatment with thionyl chloride (Scheme 2). Direct amidation of **7** with amine **3** and subsequent de-O-acetylation provided tetravalent glycocalix[4]arene **8**.

Glycocalix[4]arenes of higher valencies were synthesized by a semiconvergent approach. Divalent α-D-GalNAc precursor **5a** and its deprotected form **5b** were first obtained by treatment of amine **3** with *N*-Boc-6-aminohexanoic acid followed by trifluoroacetolysis and N-bromoacetylation to give **4** in 85% yield (see Scheme 1). Double N-alkylation of mono-*N*-Boc-1,4-diaminobutane with **4** gave dimer **5a** in 73% yield, which was deprotected to provide **5b**. Treatment of acid chloride **7** with mono-*N*-Boc-1,4-diaminobutane afforded **9** in 63% yield. Trifluoroacetolysis of **9** gave **10**, which was N,N-dialkylated with **4** to provide octavalent glycocalix[4]arene **11** in 64% yield after deprotection (Scheme 3). Octameric tetraamine derivative **13** was also obtained by double N-alkylation of **10** using 4-bromoacetamido-1-Boc-butanediamine (51%, Scheme 4). Finally, hexadecameric glycocalix[4]arene **14** was prepared from octameric amine **13** and bromoacetamido-GalNAc derivative **4** after de-O-acetylation.

The ligands **5b**, **8**, **11**, and **14** were purified by size-exclusion chromatography (Sephadex LH20, MeOH). ^{1}H NMR spec-

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[**] We thank the National Science and Engineering Research Council of Canada (NSERC) for financial support and Dr. P. Thibault, National Research Council of Ottawa (NRC), for MALDI-TOF mass spectrometry experiments.