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Gold Clusters

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Separation of Enantiomers and CD Spectra of $Au_{40}(SCH_2CH_2Ph)_{24}$: Spectroscopic Evidence for Intrinsic Chirality**

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Chirality plays a key role in nature and in the pharmaceutical sciences. The chirality of organic compounds is very often linked to the element carbon with its tetrahedral bonding structure that can give rise to asymmetric centers. Metals, on the other hand, tend to form highly symmetric structures in their bulk condensed phase. Bestowing chirality on them would be of importance in fields like enantioselective catalysis[1] and for the preparation of materials with unusual optical properties.[2] It has become evident in the last two decades that the surfaces of metals can also exhibit chirality, either intrinsically or through the interaction with adsorbates.[3]

Even more recently, chiral thiolate-protected gold particles or clusters ($Au_n(SR)_m$) have become an intensively studied field and insight in this area may guide the way towards chirality in metals. After the first observation of optical activity (hence, chirality) was reported in 1998, numerous examples were studied.[4–6] It seemed a paradigm that the strong chiroptical response was based on the use of chiral thiolates as the protecting agent. A breakthrough was the first successful X-ray structure determination of a Au_{102}(*p*-MBA)$_{44}$ cluster (*p*-MBA: *para*-mercaptobenzoic acid),[7] which revealed two surprising findings: 1) an unusual bridged binding motif between gold and sulfur (staple motif) and 2) a chiral arrangement of the staples on the cluster surface. As no chiral induction is given in this example (*p*-MBA is not chiral), both enantiomers of the cluster are found in the unit cell of the crystal. A similar situation is found for $Au_{38}(SR)_{24}$ clusters.[8]

The origin of optical activity and the contribution of different effects have been discussed, but no satisfying answer could be given yet. Different levels of chirality need to be taken into account for the observed optical activity: 1) intrinsically chiral cluster cores;[9] 2) a chiral arrangement of the staples on the surface;[5b] and 3) "external" induction of chiral information through homochiral ligands. The individual contribution of these effects may be difficult to be determined as they cannot be discriminated experimentally.

Very recently, we succeeded in the enantioseparation of Au_{38}(2-PET)$_{24}$ (2-PET: SCH_2CH_2Ph) and measured the first CD spectra of an intrinsically chiral cluster protected with achiral ligands.[10] The inherent chirality of Au_{38}(2-PET)$_{24}$ has been predicted and confirmed by X-ray analysis of single crystals.[8,11] The chirality of the Au_{38} cluster is due to a chiral arrangement of the protecting $(RSAu)_nSR$ ($n = 1,2$) staples on the surface of the Au_{23} cluster core. A very strong chiroptical response was found with an anisotropy factor of up to 4×10^{-3}; this is the highest anisotropy factor of gold clusters reported so far. Interestingly, this value is higher than that for Au_{38} with a chiral thiolate as the ligand.[4b]

As Au_{38} and Au_{102} clusters are chiral owing to the arrangement of the protecting staples and in silico studies predict chirality for $Au_{144}(SR)_{60}$,[12] the question arises whether other cluster sizes also display intrinsic chirality. $Au_{25}(SR)_{18}$ clusters have been successfully crystallized and careful analysis of the structures reveals two intertwining helices of opposite handedness; thus, the cluster can be regarded as a *meso* compound.[13] This cluster is therefore not chiral. Interestingly optical activity, although relatively weak, has also been reported for Au_{25} covered with chiral thiolates.[5h,14]

We report herein on the enantioseparation of Au_{40}(2-PET)$_{24}$ using chiral HPLC. The enantiomers were characterized by their CD spectra. $Au_{40}(SR)_{24}$ clusters have been identified as by-products in the thermal etching process towards $Au_{38}(SR)_{24}$.[5e,15] Ligand-exchange experiments suggest a Au_{26} core protected by six $Au(SR)_2$ and four $Au_2(SR)_3$ staples.[5e] To the best of our knowledge, the native cluster is uncharged and does not fulfill the magic-number rule. The electron count of the cluster is 16 and the next closed electron shell is 18.[16] Stability is therefore assigned to a nonspherical core. Larger amounts of monodisperse Au_{40} clusters are accessible by semipreparative gel permeation chromatography.[15b]

Au_{40}(2-PET)$_{24}$ was prepared and isolated as reported earlier (a detailed protocol can be found in the Supporting Information).[5e,15b] The material was characterized as Au_{40}(2-PET)$_{24}$ by UV/Vis spectroscopy and MALDI mass spectrometry (see the Supporting Information).[17] The enantiomers were then separated on a chiral cellulose-based HPLC column. In contrast to the Au_{38} case, full baseline separation was not achieved, but two peaks were identified (enantiomers **1** and **2** according to increasing elution times, Figure 1). The eluting solutions were collected over several HPLC runs, and material from the region in which the two peaks overlap most was discarded.

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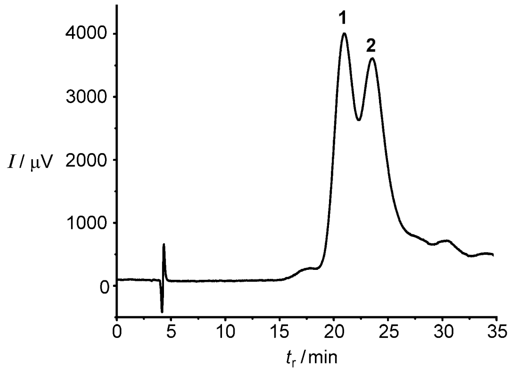

Figure 1. HPL chromatogram (hexane/2-propanol 9:1) of Au$_{40}$(2-PET)$_{24}$ at a flow rate of 1 mL min^{-1}. The two peaks at 20.9 and 23.55 min were assigned to the two enantiomers of Au$_{40}$ based on their absorption properties (see the Supporting Information).

The CD spectra of the two isolated samples exhibit an excellent mirror-image relationship over the full spectral range (Figure 2, left). Overall, nine signals can be identified (for **1**: 238 (+), 261 (−), 282 (+), 306 (+), 327 (−), 357 (+), 419 (−), 534 (+), 642 (−)). The presented data clearly show that Au$_{40}$(2-PET)$_{24}$ is intrinsically chiral. This is the first time that inherent chirality in a gold cluster was revealed without the aid of X-ray structure determination or computational studies and solely based on circular dichroism. Moreover, the CD spectra provide more information than ordinary absorption spectra on electronic transitions in Au$_{40}$ clusters. This is particularly true for Au$_{40}$ with its largely unstructured absorption spectrum (Figure 2, left) compared with, for example, the spectrum of Au$_{38}$.

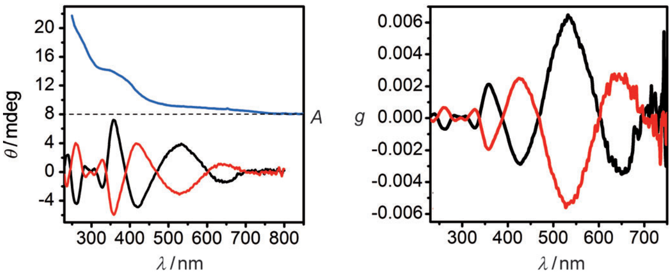

Figure 2. Left: CD spectra of the enantiomers of Au$_{40}$(2-PET)$_{24}$ (black: enantiomer **1** eluting at 20.9 min; red: enantiomer **2** eluting at 23.55 min (peak maxima)). The difference in intensity is due to the different concentrations and enantiomeric excesses in the solutions (see text). Blue: Absorption spectrum of **1** for comparison. Right: Anisotropy factors g of **1** (black) and **2** (red). The anisotropy factors are extrapolated taking into account estimated enantiomeric excesses of roughly 45 and 40% for **1** and **2**, respectively.

The intensity of CD spectra depends on the concentration of the sample, and the concentration-independent anisotropy factors $\Delta A/A$ were therefore calculated over the spectral range (Figure 2, right). The maximum anisotropy factor found is about 3×10^{-3} (at 534 nm). Because the retention times of the two enantiomers are similar, the separation is not complete and the collected fractions are not enantiopure, in contrast to Au$_{38}$ for which baseline separation was achieved.[10] This difference in separation may be related to the considerably different structure of Au$_{40}$. The enantiomeric excess (*ee*) in the collected fractions was determined by HPLC (for details, see the Supporting Information). The data in Figure 2 (right) are scaled with the estimated *ee* values. As the sum of the two extrapolated anisotropy factors is very close to zero (a test for the accuracy of the extrapolation), we are confident of its magnitude (within an error of ca. ± 10%). The maximum anisotropy factor is found for the transition at 534 nm and—to the best of our knowledge—the value of 6×10^{-3} is the largest anisotropy factor found for gold clusters, at least exceeding the value for Au$_{38}$(2-PET)$_{24}$ (4×10^{-3}).[10] The strong anisotropy may be linked with electronic transitions involving stereogenic units of the cluster (but as the structure remains unknown, this conclusion remains unsupported).

In other studies the strength of chiroptical responses of gold clusters was found to decrease with increasing cluster size.[5c,6,18] However, the presented data are contradictory to this. The absorption onset of Au$_{40}$ (ca. 800 nm) is at shorter wavelength (larger optical gap) than for Au$_{38}$ (NIR transition at 1040 nm) and we therefore were able to cover the spectral region around the HOMO–LUMO transition. Of note, little to no optical activity is found at wavelengths above 700 nm and we assume that the HOMO–LUMO transition is not optically active.

In summary, we demonstrated that Au$_{40}$(2-PET)$_{24}$ is chiral; we successfully achieved enantioenrichment of the clusters and measured their CD spectra. The fact that chiroptical responses are detectable although the protecting thiolate is achiral demonstrates the intrinsic chirality of the Au$_{40}$ cluster. Such chirality may arise through the chiral arrangement of staples, such as in Au$_{38}$(2-PET)$_{24}$. Compared to the rather featureless absorption spectrum of Au$_{40}$(2-PET)$_{24}$, the CD spectrum of Au$_{38}$(2-PET)$_{24}$ is rich in information, which may serve in determining the cluster structure based on comparison with theory. Moreover, we found an anisotropy factor with a maximum value of about 6×10^{-3}, which is the largest value reported for gold clusters so far. The extent of the chiroptical response exceeds the values found for enantiopure Au$_{38}$(2-PET)$_{24}$.

Experimental Section

The origin of materials and detailed synthetic procedures and chromatographic methods are described in the Supporting Information. The Au$_{40}$ cluster was prepared, purified and size-selected as described earlier.[5c,15b]

UV/Vis spectra were recorded on a Varian Cary 50 spectrophotometer (1 cm pathlength, CH$_2$Cl$_2$). Mass spectra were obtained using a Bruker Autoflex mass spectrometer equipped with a nitrogen laser at near-threshold laser intensity in linear mode. DCTB was used as the matrix.[17] CD spectra were recorded on a JASCO J-815 spectrometer (5 mm pathlength, CH$_2$Cl$_2$, 20 °C). Eight scans were averaged. Anisotropy factors $g = \Delta A/A = \theta$-[mdeg]/(32980 A) were determined using the UV/Vis spectra provided by the CD spectrometer.

The enantiomers were separated chromatographically on a JASCO 20XX series HPLC system equipped with a Phenomenex Lux-Cellulose-1 column (5 µm, 250 × 4.6 mm). For detection, a JASCO 2070plus UV/Vis detector was used at a detection wavelength of 380 nm. The analytes were eluted at a flow rate of 1 mL min^{-1} (hexane/2-propanol 9:1).

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