

Dumbbells, Trikes and Quads: Organic–Inorganic Hybrid Nanoarchitectures Based on "Clicked" Gold Nanoparticles

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 \boldsymbol{T} he controlled assembly of gold nanoparticles in terms of the spatial arrangement and number of particles is essential for many future applications like electronic devices, sensors and labeling. Here an approach is presented to build up oligomers of mono functionalized gold nanoparticles by the use of 1,3-bipolar azide alkyne cycloaddition click chemistry. The gold nanoparticles of 1.3 nm diameter are stabilized by one dendritic thioether ligand comprising an alkyne function. Together with di-, tri- and tetra-azide linker molecules the gold nanoparticle can be covalently coupled by a wet chemical protocol. The reaction is tracked with IR and UV-vis spectroscopy and the yielded organic-inorganic hybrid structures are analyzed by transmission electron microscopy. To evaluate the success of this click chemistry reaction statistical analysis of the formed oligomers is performed. The geometric and spatial arrangements of the found oligomers match perfectly the calculated values for the used linker molecules. Dimers, trimers and tetramers could be identified after the reaction with the corresponding linker molecule. The results of this model reaction suggest that the used click chemistry protocol is working well with mono functionalized gold nanoparticles.

1. Introduction

Gold nanoparticles (Au NPs) are intensively studied as easy accessible model compounds and functional units in various applications. Au NPs are utilized for example in catalysis,^[1,2] sensor application,^[3] nano-electronic devices^[4,5] and labeling.^[6–9] For most of these applications a controlled assembly of Au NPs into defined architectures is essential and several

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review articles highlight the importance of this research field.^[10-13] Various concepts were developed in order to connect Au NPs into more complex structures by exploiting different binding concepts. The use of π - π interactions,^[14] hydrogen bonding,^[15-17] charge transfer^[18] or coordinative bonds^[19] were investigated. The use of host-guest interactions^[20-23] and DNA recognition subunits^[24-33] were also used to build up well defined assemblies of nanoparticles. Covalent bonds are among the most stable ways to assemble Au NPs into complex structures. A widely used tool to interlinke Au NPs or to decorate their surface is the Cu(I) catalyzed "Sharpless click reaction".^[34] as the mild room temperature version of the Huisgen 1,3-dipolar cycloaddition between azide and an alkyne forming a 1,2,3-triazole. The covalent interlinking of Au NPs has been used for the optical detection of copper by color change of Au NP solutions or by precipitation after forming huge networks.^[35–38] The detection of proteins has been achieved by using functional Au NPs, which create large assemblies resulting in an optical response.^[39,40] Au NPs were also assembled by click chemistry to form photo responsive networks,[41] liquid



Figure 1. 3D sketch of the click reaction and the resulting oligomers. **G2** stabilized Au NPs (left) are clicked together with benzyl azides (middle) into dimers, trimers and tetramers (right).

crystals,^[42] oligomers,^[43] chains,^[31] combined networks of metal nanoparticles^[44,45] and robust nanostructures of different shapes of Au NPs.^[46] Furthermore the assembly of Au NPs via click chemistry on functionalized metal and polymer surfaces was performed.^[47–51]

These approaches were usually controlled by the maximum number of reactants fitting around one NP or were performed in a statistical fashion. Our goal is to obtain welldefined oligomers of Au NPs in means of spatial arrangement and number of NPs within each assembly. To obtain such structures the ideal Au NP would be characterized by three key features: good chemical stability, narrow size-distribution and well controlled number and spatial arrangement of functional groups exposed at its surface. In 2008 our research group presented the formation of stable Au NPs stabilized by octadentate thioether ligands.^[52] It was found that two ligands are coating the NP's surface, leading to bifunctional Au NPs upon introduction of a functional moiety into the ligands backbone.^[53] These functional NPs carrying two terminal protected acetylenes were coupled to form organic/ inorganic superstructures by applying a wet-chemical oxidative acetylene homocoupling protocol.^[54] In order to create monofunctionalized NPs, larger dendritic ligands were designed. Exactly one second generation dendrimer consisting of 20 thioether moieties was able to stabilize an entire Au NP^[55] leading to monofunctionalized Au NPs, which were used to form dumbbell structures by oxidative acetylene coupling.^[56] These alkyne-monofunctionalize Au NPs can be considered as artificial molecules and in order to further explore the range of applicable reactions, we became interested in the copper catalyzed mild click reaction between alkynes and azides.

Here we present the assembly of organic/inorganic hybrid architectures by interlinking mono-alkyne functionalized Au NPs with small oligoazide functionalized linker structures using click chemistry. In particular our attempts to assemble dimers, trimers and tetramers are reported.

2. Concept and Strategy

The dendritic thioether ligand **G2** (Scheme 1) efficiently stabilizes Au NPs of a size of about 1.3 nm. The Au NPs are formed by reduction of choloro auric acid in present of the ligand G2. While this reduction the growing Au NPs are enwrapped by the dendritic ligand that stabilizes and traps the Au NPs with an almost monodisperse size distribution around 1.3 nm that is given by the size of ligand's cavity. One G2 dendrimer bearing a triisopropylsilyl (TIPS) protected acetylene moiety is capable to stabilize an entire Au NP (Au/G2) and for that reason provides full control over the chemical reactivity of the organic shell surrounding the Au/ G2.^[55,56] The acetylene moiety is attached

to an oligo phenylethylene (OPE) rod in order to have the functionality in the NP's periphery. A pyridine moiety was chosen as anchor of the OPE to the NP surface because it is known to provide a fixed perpendicular arrangement of the OPE spacer on the Au NP surface.^[54] This rigid arrangement increases the spatial control over the NPs forming the organic/inorganic hybrid structure. Click chemistry seems particularly suited to covalently assemble the monofunctional Au NPs Au/G2 in well-defined structures. The mild conditions of this well-known azide-alkyne click chemistry reaction make it perfect candidate for this purpose. All reagents used to catalyze this 1,3-bipolar cycloaddition are easily removed after the reaction by aqueous workup. In order to perform click chemistry azide functionalities have to be installed at the periphery of the interlinking structure. By the number of the installed azide moieties, the size of the interlinking structure and their geometric arrangement full control is gained over the number of linked particles and their spatial arrangement. Here benzyl azides are investigated due to the easy synthetic accessability of this functional group and its known reactivity in click reactions. On the one hand rotational freedom around the benzvlic carbon-carbon bond is expected to provide an increased reactivity because the huge particles can evade each other and do not cause sterical hindrance. One the other hand the distance between the particles can differ more if they can form varying arrangements around the linker molecules. However, the difference in the distance should be small enough that a statistical evaluation by transmission electron microscopy (TEM) imaging is still possible. Different numbers of benzylic azides evenly arranged on a central benzene ring are expected to direct the assembly of Au NPs into unique geometric arrangements, which can be observed by TEM investigations. Figure 1 sketches the concept of controlling the spatial assembly of the interlinked NPs by the azide substitution pattern of the linker.



Scheme 1. Synthesis of ligand G2 using literature known fragments G1[SH] and 1.

3. Synthesis

3.1. Synthesis of the ligand

The **G2** dendrimer, which is used to stabilize the Au NPs, was synthesized from literature known dendron [**G1.SH**] and the functional OPE rod (1, see **Scheme 1**).^[56]

To yield **G2** two equivalents of **[G1.SH]** were reacted with one equivalent of the OPE rod (1) in tetrahydrofurane (THF) with sodium hydride (NaH) as base. After aqueous workup and purification with silica column chromatography and finally recycling gel permeation chromatography (GPC) the dendritic ligand was obtained as colorless oil in good yields.

3.2. Synthesis of the Multi-Triazide Functionalized Linkers

The azide functionalized linker molecules 2-4 were synthesized by a classical $S_N 2$ reaction following a reported protocol. The benzylbromide derivative of interest was treated with an excess of sodium azide (approximately 25 equivalent) as 0.5 M solution in dimethylsulfoxide (DMSO) (Scheme 2).^[57] After stirring for 18 h, the reactions were quenched and washed five times with water to remove remaining DMSO. The crude products were purified by column chromatography. Those compounds were obtained in quantitative yields and were stable at ambient conditions for several days. Starting from 1,4-bis(bromomethylene) benzene **5** the 1,4-bis(azidomethylene)benzene **2** was obtained as colorless oil. The 1,3,5-tris(azidomethylene)benzene 3 was synthesized from 1,3,5-tris(bromomethylene)benzene 6 as colorless oil. The 1,2,4,5-tetrakis(azidomethylene) benzene 4 was isolated as colorless solid starting from 1,2,4,5-tetrakis(bromomethylene)benzene 7. The literature known azides 2-4 were characterized by ¹H- and ¹³C NMR, mass spectrometry (MS) and match the reported data.^[58-60]

3.3. Synthesis of the Au NPs

The Au NPs were synthesized in presence of the dendrimer **G2** in a H_2O/CH_2Cl_2 solvent mixture following a protocol by

Brust et al.^[61] Hydrochloroauric acid was solved in H₂O and then transferred into the organic phase by adding tetraoctylammonium bromide (TOAB) as phase transfer agent in CH₂Cl₂. The dendrimer G2 solved in CH₂Cl₂ was added to this mixture and stirred for 15 min. Subsequently a solution of sodium borohydride in H₂O was added as reducing agent leading to an immediate color change to dark brown indicating the formation of Au NPs. This mixture was stirred additional 30 min. After aqueous workup and removal of ligand excess by gel permeation chromatography (GPC) the size of the Au NPs was determined by UV-vis and TEM. The UVvis was measured in CH₂Cl₂ and showed a very weak plasmon band at 520 nm, indicating Au NPs with a size below 2 nm. The features of the OPE rod were observed at 280 nm (Figure 2). A diluted sample was transferred on a carbon coated copper grid (CCCG) to determine the particle size by TEM images. Small Au NPs with a narrow dispersity were observed on the TEM pictures from which the size was measured by an



Scheme 2. Synthesis of azide linker molecules 2-4.

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Figure 2. UV-vis spectra to monitor the click reaction.

automatic investigation method using the software ImageJ.^[62] As recently published, the yielded Au NPs show narrow size distribution with a mean diameter of 1.3 ± 0.4 nm.^[56] Similar diameters were found for related ligand-stabilized NPs systems based on unfunctionalized thioether dendrimers or linear thioether ligands.^[52–54,63] The 1/1 ratio of stabilizing ligand per Au NPs was corroborated by thermogravimetry. As only one ligand is coating the entire Au NP, only one functional group is exposed per Au NP. It is noteworthy that similar monofunctionalized NPs formed exclusively dimers upon oxidative coupling conditions, further supporting the hypothesis of monofunctionalized Au NPs.^[56,64]

3.4. Interlinking of the Monofunctionalized Au NPs

The oxidative homocoupling of the acetylene functionalized particles in recent publications was conducted with ${\rm Cu}({\rm I})$



Scheme 3. Synthesis of nano-scale objects by wet-chemical assembly of mono-ethynyl functionalized nano-particles and the azide linkers 2–4 under "click-chemistry" conditions. Synthesis of a "dumbbell" dimer A), a trimer B) and a tetramer C); (the particle coating dendritic ligand is only sketched as formula to increase clarity).

as catalyst in stoichiometric amounts. In order to favor the cycloaddition and avoid homocoupling as competing reaction, a protocol was used with a low concentration of Cu(I) as active catalytic species which was formed in situ by reduction of Cu(II) by sodium ascorbate. As test reaction the Au NPs were exposed to all reagents in CH_2Cl_2 and CH_2Cl_2/H_2O mixtures in order to investigate the stability of the NPs under the reaction conditions. No precipitation or changes in the UV–vis spectra were observed during this treatment. Also subsequent TEM investigations showed a similar size distribution as the initial sample, pointing at the stability of the particles under the reaction conditions of interest.

The synthesis of NP oligomers by interlinking the ethynyl-exposing NPs with the oligoazides 2-4 is displayed in Scheme 3. First the Au NPs were dissolved in CH₂Cl₂ and the TIPS protection group of the ethynyl function was removed by fluoride ions coming from subsequently added tetrabutylammonium fluoride (TBAF). The reaction was quenched after 1 h and washed with water. After these deprotected AuNPs exposing a free ethynyl group were dried and redissolved in CH₂Cl₂, an equivalent of triazides was provided by adding the required amounts of the multi-triazide linker dissolved CH₂Cl₂. Thus 1/2 equivalent 2, 1/3 equivalent 3 and 1/4 equivalent 4 were added respectively. Subsequently a 1 M CuSO₄ solution in followed by 25 mol% sodium ascorbate as 1 M solution in water were added to the vigorously stirred reaction mixture. For the reactions of all linker molecules a similar analytical procedure was applied. First a sample of the CH₂Cl₂ phase was taken and investigated by UV-vis spectroscopy to monitor the Au NPs size (Figure 2). No increase in intensity or shift of the plasmon band was observed pointing at the structural integrity of the Au NPs under the applied reaction conditions. In contrast to that the signal of the OPE structure around 280 nm displayed a pronounced increase in intensity together with a slight shift to longer wavelength. These spectral changes point at an increased delocalization of the π -system, as it is expected by the formation of the triazole heterocycles as products of the "click-chemistry".

The click reaction was further monitored by attenuated total reflectance infrared spectroscopy (ATR-IR) where mainly the consumption of the azide linker was observed (**Figure 3**). The triazide band at 2100 cm⁻¹ decreased to a very small remaining trace showing the almost complete transformation of the triazide group during the course of the "click" reaction.

Finally the reaction was stopped by allowing the two phases to separate and the dark brown reddish colored CH_2Cl_2 phase was dried over MgSO₄.

4. TEM Analysis

The solved coupled Au NPs were further diluted by approximately a factor of 1000. This diluted solution was spotted on a CCCG in order to investigate structural features of the reaction products by TEM. Of particular interest are sizes, distances and spatial arrangements of Au NPs. While the first parameter mainly allows analyzing the NPs' stability, the



Figure 3. Normalized ATR-IR Spectra to monitor the decrease of azide groups (2100 cm⁻¹).

latter two reflect dimensional details of the hybrid architecture. Thus TEM analyses were ideally suited to investigate the nature and the ratios of the formed hybrid oligomers. In all three samples of the reactions with the respective linker molecules the NP sizes maintained pointing at their stability in the applied reaction conditions. The yield of the obtained NP oligomers was counted on randomly recorded TEM pictures of very diluted solutions. High dilution was chosen to minimize wrong hits eventually emerging from agglomerating hybrid objects and/or NPs, which might result in similar inter NP spacing as the desired hybrid objects. On these diluted micrographs all particles where counted and the amount of oligomeric architectures was determined manually. A set of NPs was considered as a hybrid architecture if their lateral separation was within the distances d_{max} given by the following considerations. In order to determine d_{max} the maximal expansion of the interlinking molecular structure was analyzed. These structures combine the functional units of the NPs fused to the corresponding linker molecule and were created with the software SPARTAN V4.1.1 and shown as simplified drawing in Figure 4. The modeled structures are called ms2, ms3 and ms4. To determine their maximal extensions d_{max} the OPE structures were rotated around the benzylic C-C bond until the maximum possible distance between two terminal N atoms of the structure was found (Figure 4).

In order to consider potential imprecision of the TEM images, the obtained maximum distance between both terminal nitrogen's was increased by 0.4 nm, which is the size of almost two pixels. So two particles were considered as connected if their distance d_{max} was within the calculated value $d_{\text{max}} = 3.9$ nm for **ms2**, $d_{\text{max}} = 3.8$ nm for **ms3** and $d_{\text{max}} = 3.9$ nm for **ms4**. For the statistical evaluation all distances of Au NPs fitting this selections rule were counted. Also the ratio of different oligomers was investigated for each sample.



Figure 4. Schematic drawing of model structures ms2, ms3 and ms4 to determine maximum possible distance d_{max} between two NP

4.1. Dimer Structures

The linker molecule 2 carrying two benzylic azide functions assembles NP with a maximum interparticle distance of d_{max} = 3.9 nm. To yield as many desired dimers as possible 0.5 eq. of 2 were reacted with 1 eq. Au NPs. On TEM images 249 particles were counted. 94 NPs were found as single structures, 128 NPs assembled as dimers, 12 NPs as trimers and 16 NPs within higher oligomers (Figure 5A). Trimers and tetramers can occur because of aggregation of the Au NPs. The found trimers can be the aggregation product of three single Au NPs or more likely because of the high dilution one dimer and a monomer. The tetramers are also aggregates of either a dimer with two monomers on each side or two dimers. Over all about 51% of the counted particles show the expected formation of dimers (Figure 5C). The high amount of single structures points at particles lacking an exposed and reactive acetylene group. As NMR studies document the completeness of the deprotection reaction, potential hypotheses are either sterical shielding by the large NP or competing degradation of the acetylene during the course of the coupling reaction.

The interparticle distance d measured of the oligomers display mean value of 2.9 nm calculated by a Gaussian fit (Figure 5B). All distances of particles matching the selection rule mentioned above are taken in account.

4.2. Trimer Structures

The evaluation of the click reaction with linker molecule **3** was performed following the same procedure. To yield the



Figure 5. A) Distribution of the formed oligomers, B) Distance distribution between the oligomer forming particles with Gaussian fit (red curve), C) Representative TEM pictures of formed dimer with linker molecule, more pictures are displayed in the supporting information (Figures S3, S4), D) Zoom with overlayed 3D sketch of proposed structure.



Figure 6. A) Distribution of the formed oligomers, B) Distance distribution between the oligomer forming particles comprising a Gaussian fit (red curve), C) Representative TEM pictures of formed trimers with linker molecule **3**, additional TEM records are displayed in the supporting information (Figures S5, S6), D) Zoom with overlayed 3D sketch of the proposed structure.

desired trimers equimolar ratios of azide groups in linker molecule 3 and Au NPs were mixed together under click conditions. The calculated maximum distance $d_{\text{max}} = 3.8 \text{ nm}$ of the clicked triangular structure ms3 is just slightly shorter than the distance of the clicked assembly formed by ms2. For this arrangement the third NP would form an isosceles triangle if the other two are in a stretched arrangement. Therefore smaller distances are expected as three NPs should form an equilateral triangle for less sterical repulsion. A total of 264 NPs were evaluated, of whom 104 were present as monomers, 22 arranged in dimers, 117 connected to trimers (Figure 6A) and 21 lying together as higher oligomers. The found dimers are probably linkers that only reacted with two Au NP, which seems the more likely scenario than two aggregated Au NPs, considering the high dilution deposition protocol. The found tetramers are supposed to be aggregates of trimers with a single Au NP. Again a reasonable amount of monomers could be observed. Because of the low ratio of dimers a passivation of the linking structure during the reaction must occur. If only sterical reasons would cause this distribution a higher amount of dimers would be expected. The coupling reaction is relatively fast as no further increase in the yield of oligomers is observed after 2 h. This observation further favors the hypothesis of competing side reactions over solely sterical arguments.

A clear trend can be observed as about 44% of the nanoparticles were found in triangular assemblies (Figure 6C). The distance distribution measured from TEM is broader than the first sample and shows a smaller mean interparticle distance of 2.4 nm (Figure 6B). The broadening can be explained by the higher flexibility of three possible rotations around the benzylic C–C bond leading to a larger variety of NPs spacing.

4.3. Tetramer Structures

Subsequently the click reaction of an equimolar amount deprotected NPs with linker molecule 4 was examined. The maximum length d_{max} of ms4 was calculated to be 3.9 nm, which is the same as the stretched conformation of the interlinking structure ms2. For interlinked substructure ms4 a rectangular shape with two different sides (Figure 8) is expected. Just the four sides were measured for the evaluation of the interparticle distance; the diagonals were not taken in account. This procedure was applied because also dimers and trimers where measured. In the case of the trimers it cannot be distinguished whether a edge or diagonal distance is measured. To measure a equal representative amount of distances all four edges of a tetramer structure were considered without the diagonals. For a dimer one distance is measured, for a trimer three distances and four distances for a tetramer. The diluted TEM images of the clicked samples displayed nanoparticles present as monomers, dimers, trimers and tetramers without a clear peak for the desired oligomer as in the first experiments (Figure 7A). Again about 30% of the Au NPs were present as monomer structures what is in analogy with the previous reactions. One difference in this case is the decreasing number of found oligomers that is a hint for additional restraining effects. Our hypothesis is that this might be due to the limited space around the linker molecule 4. This is leading to a higher yield of undesired dimers and trimers instead of tetramers. The first two NPs probably react in the same manner as for linker molecule 2 because the additional benzylic azides are not very sterical demanding. As soon as two NP are attached to linker 4 both remaining azides are already shielded by the present NPs hindering the next reaction step to the trimer. The reaction of the trimer to the tetramer is even more hindered, as the linker molecule

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Figure 7. A) Distribution of the formed oligomers, B) Distance distribution between the oligomer forming particles with a Gaussian fit (red curve), C) Representative TEM pictures of formed tetramers with linker molecule **4**, more TEM pictures are displayed in the supporting information (Figures S7–S9), D) Zoom with overlayed 3D sketch of proposed structure.

is rather small compared to the particles. Therefore, the formation of tetramers is not favored and an equal distribution of oligomers was obtained. Of 299 NPs that were evaluated for the investigation 131 of them were present as monomers. 98 NPs were present as dimers, 93 as trimers and 64 NPs were reacted to tetramers (Figure 7A). Extended duration of the click reaction could not improve the ratio of the oligomers towards more tetramers. The mean distance for all oligomers stated as connected to each other is 2.4 nm (Figure 7B).

4.4. Discussion of the Measured Distances

All found interparticle distances are all considerably shorter than the calculated maximum possible spacing. This behavior was expected because the maximum distances d_{max} were calculated to define a selection rule in order to determine particles as coupled to each other. In reality the spacing between the particles must be shorter because the interlinking structure will arrange in a more folded geometry (**Figure 8**).



Figure 8. Energy minimized model (MMFF94) structures *ms2*, *ms3*, and *ms4* in stretched out geometry representing the expected maximum spacing between Au NPs interlinked by the molecules 2, 3, and 4 respectively.



Figure 9. Sketch to visualize calculations for Au NP inter particle distances. Left side dimer structure, middle trimer structure and right tetramer structure. All lengths are calculated by using molecular mechanics (MMFF94) from *ms2*, *ms3*, and *ms4* (see Figure 8).

An approximate value to evaluate the experimental found distances was calculated for each click reaction. The dimer structure **ms2** is able to rotate around both benzyl C – C bounds what leads to various stretched and folded conformation of interlinked particles. The minimum distance for the folded conformation is calculated to be $l_{1 \text{ fold}} = 1.3 \text{ nm}$ for the stretched conformation a maximum value of $l_{1 \text{ stre}} = 3.2 \text{ nm}$ is calculated. The mean diameter of all found dimers show a nice distribution from 1.3 nm to $d_{\text{max}} = 3.9 \text{ nm}$ with its mean value at 2.9 nm. Because of the huge size and the resulting repulsion of the Au NPs a stretched assembly is more probably. That is reflected in the found distance d = 2.9 nm which is at the upper end of the possible calculated value matching nearly calculated distance for a stretched assembly.

In contrast to the above discussed stretched dimers, the measured interparticle distances in trimers and tetramers is no longer directly reflecting the interlinking structure and its correlation must thus be corrected. For the trimer structure a flat arrangement like an equilateral triangle is expected. This arrangement would provide a maximum of space for each coupled Au NP. From a MM2 relaxed planar fixed model of structure *ms3* the distance d_{calc} for an equilateral triangle is calculated with equation (1).

$$d_{calc} = \frac{l_2 \cdot (l_2 + r)}{l_2} - 2r \tag{1}$$

The value l_1 is measured form the coupled structures center *ms3* to the nitrogen atom of the clicked OPE rod of the ligand **G2** and l_2 from one nitrogen atom to the next neighbored in this structure (Figure 8). With the radius *r* of the Au NPs the distance *d* can be calculated by applying the intercept theorem as displayed in **Figure 9** using equation (1). The found mean distance *d* of 2.4 nm matches the calculated value d_{calc} of 2.4 nm perfectly. Of course the distances can vary when the structure is rotated around the benzylic C–C bounds from a minimum value of 1.3 nm to a maximum value of 3.1 nm that is well reflected in the distance distribution (Figure 6B). The perfect matching of the calculated value d_{calc} with the measured distances d fully supports the hypothesis of formed trimers and their flat relaxed arrangement as equilateral triangle on the CCCG of the TEM.

In similarity to the trimers above, a flat arrangement is also assumed for the tetramer structures on the CCCG. For the rectangular structures ms4 the two different sides l_{2A} and l_{2B} must be taken into account. The calculated inter particle distances d_A and d_B are calculated from the values l_{1A} , l_{2A} , l_{1B} , l_{2B} and r (Figure 8) with formula 1 in the same manner as for the triangle structures (Figure 9). The measured mean distance of 2.4 nm matches calculated mean distance 2.4 nm of $d_A =$ 2.2 and $d_{\rm B}$ = 2.7 for a flat assembly perfectly (Table 2). The fact that the measured distances of the reaction to tetramers matches the calculated values supports

the hypothesis that also the found dimers and trimers arise from not completely reacted linker molecules, because they assemble in similar distances to each other. These results reflect the flat arrangement of the tetramer structures as well as the hypothesis of the high amount of dimers and trimers caused by sterical repulsion of the Au NPs during the click reaction. All values for the calculation are listed in **Table 1**.

In **Table 2** the experimental found and calculated distances are summarized for all synthesized Au NP oligomers.

In summary, the observed nanoparticle oligomers reflecting the numbers and spatial orientation of the functional groups of the oligoazide precursors, the interparticle distance analysis in the obtained organic/inorganic hybrid

Table 1. All calculated lengths for l_1 , l_2 , l_{2A} , l_{2B} by 3D model using molecular mechanics (MMFF94) and measured radius of Au NPs by TEM.

	Dimer [nm]	Trimer [nm]	Tetramer [nm]
l_1	3.2	1.6	1.6
l_2	х	2.6	х
l_{2A}	х	х	2.1
l_{2B}	х	х	2.7
r	0.6		

Table 2. Maximum distance for particles count as oligomer, average experimental found distance, calculated distance value form energy minimized model (MMFF94).

Distance [nm]	Dimer	Trimer	Tetramer
Maximum Distance d_{\max}	3.9	3.8	3.9
Found Distance d	2.9	2.4	2.4
Calculated Distance d _{calc}	3.2	2.4	2.4 ^{a)}

^{a)} For tetramers two different distances of NP neighbors (2.1 nm) and NP on opposite sites (2.7 nm) can be expected. Mean value of both distances calculated for the tetramer.

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architectures, and the disappearance of the azide bands in the IR spectra are corroborating the successful interlinking of the ethynyl functionalized particles by "click chemistry". The UV–vis spectra further support the formation of triazole linkers and corroborate the stability and homogeneity of the ligand coated gold nano-particles under the applied reaction conditions.

5. Conclusion

The formation of Au NPs into defined organic/inorganic hybrid nanoarchitectures in means of quantity and spatial arrangement utilizing a wet click chemistry protocol is successfully demonstrated with mono acetylene functionalized Au NPs. A series of azide linker molecules was used to build up dimer, trimer and tetramer structures reflecting the linker's geometry. Our current attempts are geared towards optimizing the reactive sites for the Huisgen 1,3-dipolar cvcloaddition in order to improve the efficiency of the coupling reaction. We are searching also for ligand structures providing larger monofunctionalized metallic particles displaying plasmon resonance bands which are of interest for a variety of optical experiments and devises. Finally strategies to improve the stability of the particles are very appealing as the diversity of applicable reactions scales with the stability of the reacting species.

The proof of concept to use Au NPs as artificial molecules engaged in click reactions is appealing for numerous applications ranging from labels to functional units in electronic and optical devises. The future success of the approach however will depend strongly on the nature, variety, and quality of available particles.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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