Doctoral (*Ph.D.*) theses

Syntheses, structural characterizations and sensor applications of gold nanoparticles and nanoclusters

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1. Introduction

In the last years, the synthesis and characterization of noble metal nanostructures (mainly gold and silver) became increasingly in the focus thanks to their shape-, size- and composition-dependent optical properties. These nanostructures are widely used in different ways from the electronics through the catalysis to the medical applications. The well-known chemically inert feature of gold is present in the nanometre size range as well. In addition, it is a widely studied nanostructured material due to its increased reactivity compared to the bulk phase and its unique optical features named localized surface plasmon resonance (LSPR).

In the field of the biomedical applications, beside the selectively functionalized gold nanoparticles (Au NPs) and the fluorescent sub-nanometre sized gold nanoclusters (Au NCs) are getting more and more attention because they exhibit high kinetic stability in physiological conditions. During these biocompatible synthesis procedures only one biomolecule acts both as a reducing and a stabilizing agent and different nanostructures (NPs or NCs) can be synthesized depending on the applied molar ratio of gold precursor ions (e.g. aurate) and the biomolecule. Namely, the application of equivalent or small biomolecule excess results in the formation of colloidal Au NPs ($d > 2$ nm) which possess characteristic size- and shape-dependent plasmon resonance band in the UV–Vis spectra. In contrast, for the utilization of high biomolecule excess subnanometer-sized Au NCs are formed ($d < 2$ nm). Besides the molar ratio of the reactants, the pH used in the synthesis also plays a determining role in the optical properties of the above mentioned nano-objects. The ultra-small Au NCs show unique physical and chemical properties such as well-defined molecular structure, discrete electronic transitions and characteristic strong structural-tuneable photoluminescence (PL). Their remarkable quantum yield makes it possible to use them as fluorescent markers but they can also serve as the basis of fluorescent biosensors.

2. Aims

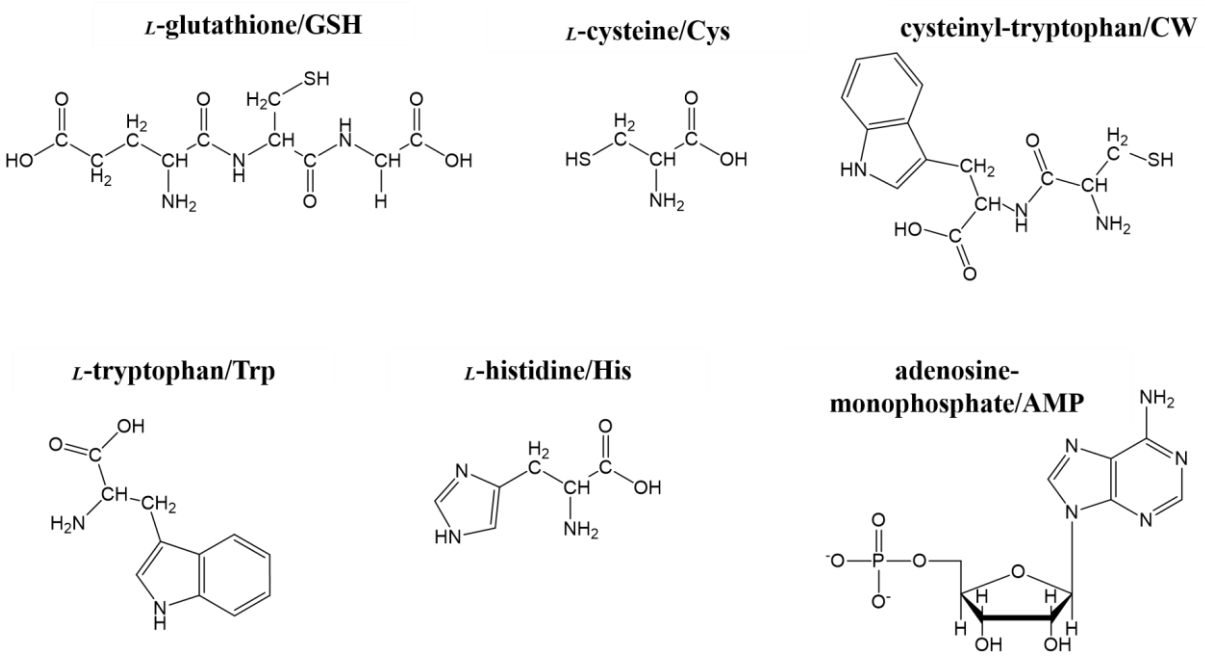
In our research group, the development of biocompatible syntheses of plasmonic Au NPs and fluorescence Au NCs as well as the characterization of the produced gold/biomolecule hybrid systems are in focus of extensive research: study the relationship between the structure and their optical properties and investigation of their potential utilizations. In the autumn of 2014, I joined to the research group in the frame of the Catalysis, Surface, Colloidal and Material Science program of the Chemistry Doctoral School at the University of Szeged. In the first period, the interactions of thiol-containing proteins and small molecules with tetrachloro-

aurate ions have been investigated in aqueous medium. Furthermore, the experimental studies have been extended to the aromatic N-containing biomolecules as well. The aim of the work was to develop reproducible synthesis methods where gold nanohybrid systems having well-defined optical properties can be formed as products. We wanted to determine the critical parameters of the syntheses (molar ratio of reactants, pH, time, *etc*.) as well as to widely characterize the stable nanodispersions and fluorescence hybrid structures. For some systems, we have also proposed their possible applications for medical diagnostic and sensor field.

Furthermore, one of the main motivations of the doctoral dissertation was that although several international research groups are involved the synthesis and characterization of noble metal NCs but only 2–3 Hungarian research groups focus their research on the investigations of the structure-dependent optical features of nanoclusters. With the results of our research we wanted to contribute to the multiplicity of this topic.

3. Syntheses and methods

The chemicals have analytical purity and were used without further purification. Each stock solution and the metal dispersions were freshly prepared with ultra-pure, boiled and carbon free MQ-water (Millipore, Milli-Q Integral3, conductivity 18.2 mS/cm at 25 °C). The experimental parameters of the syntheses are presented as new scientific results. The structural formula of the small biomolecules which were used as reducing and stabilizing agents, with the exception of proteins, are summarized in **Figure 1**.



1. Figure: The structural formula of the applied biomolecules.

The prepared nanohybrid systems were characterized by the following measurement techniques:

- UV-visible spectrophotometry (Shimadzu UV-1800)
- Fluorescence spectroscopy (Horiba Jobin Yvon Fluoromax-4)
- Fluorescence lifetime and quantum yield (Edinburgh FLS920)
- Fourier-transformed infrared spectroscopy (BIO-RAD Digilab Division FTS-65A/896 and BIO-RAD Digilab Division FTS-40)
- Circular dichroism spectroscopy (JASCO J-1100)
- Mass spectrometry (Waters-Micromass and Bruker Reflex II)
- Dynamic light scattering and ξ-potential measurements (Malvern NanoZS)
- High resolution transmission electron microscopy (FEI Tecnai G2 20 X-Twin)
- X-ray electron spectroscopy (SPECS XR50 X-ray tube and PHOIBOS 150 MCD 9 analyzer)
- X-ray powder diffraction (Bruker D8)
- Small angle X-ray scattering (Philips PW 1820 X-ray tube, KCEC/3 Kratky Camera and PDS 50M detector)
- Fluorescence microscopy (Leica DM IL LID FLUO with 100 W HBO lamp)
- Freeze-drying (Christ-Alpha 1-2 LD)
- Isothermal titration calorimetry (MicroCal)

4. New scientific results

T1. *Size-controlled syntheses and structural characterization of lysozyme-stabilized Au nanoparticles and nanoclusters* [1].

• The LYZ protein was successfully applied to reduction of $AuCl_4^-$ ions in aqueous medium at 37 ºC. The weight ratios of the components was systematically changed in the alkaline medium, whereupon both plasmonic Au NPs (LYZ:Au/5:1) and fluorescent Au NCs (LYZ:Au/20:1) were fabricated. The size of the metal particles showed downward trend by increasing the amount of the protein. Studying the optical properties and the size of the nanoproducts, it was found that the plasmonic band of the LYZ-Au NPs appeared at 518 nm and the average size was 12.0 ± 3.1 nm based on the TEM images. The fluorescence LYZ-Au NCs had characteristic emission band in the red range of visible light (λ_{em} = 655 nm) instead of the plasmonic feature and their average diameter was 1.5 ± 0.3 nm based on the electron microscopic measurements.

- After the lyophilisation, both the LYZ-Au NCs and the LYZ-Au NPs could be stored even 1 year and they could be redispersed without aggregation. Based on the structural measurements using SAXS and FT-IR techniques, it was determined that the change in the secondary structure of the protein showed same results in case of both techniques. From the Kratky representation of the SAXS scattering curves, it can be concluded that the protein had a partially unfolded structure after the formation of LYZ-Au NPs. In case of the LYZ-Au NCs the fully unfolded conformation of the protein was identified, which was supported by the location of the Amid I band (1648 cm^{-1}, random coil) on the FT-IR spectra.

T2. *Size-controlled synthesis of Au nanoparticles and nanoclusters using γ-globulin immunoprotein. Sensor application of γG-Au NCs for fluorimetric detection of L-kynurenine.*

- We confirmed that, the application of γG immunoprotein as reducing and stabilizing agent results in the formation of both gold nanoparticles and nanoclusters. The Au NPs prepared at γG:Au/1:1 weight ratio showed plasmonic band at λ_{max} = 525 nm and their average size was 24.2 ± 12.3 nm. Au NCs synthesized at γG:Au/15:1 weight ratio exhibit characteristic red fluorescence at λ_{em} = 645 nm and monodisperse distribution of the NCs with 1.5 ± 0.3 nm average size was obtained.
- The FT-IR and CD spectroscopic measurements indicated that the secondary structure of the protein during the cluster formation was changed: the mainly β-sheets was transformed into β-turns and random coils. The γG-Au NCs showed high kinetic stability under physiological conditions.
- The γG-Au NCs were successfully applied as potential L-kynurenine (Kyn) biosensor. It was found that, the measurable change of the fluorescence was detected in case of only the first metabolic molecule (Kyn) of the kynurenine pathway. The sensor measurements were carried out at 4 different temperatures (298, 303, 308 and 310 K). For more detailed understanding of the interaction, the analytical and thermodynamic parameters were determined. In case of the Kyn the limit of detection (LOD) of 15 μM and the dynamic range of 15–100 μM were obtained. Based on the measurement data the quenching process was dynamic, thermodynamically favourable, entropy-driven and endotherm. Even, a charge transfer between the clusters and the Kyn may occurs.

T3. *Syntheses and structural characterization of Au nanohybrid systems using thiol-containing small biomolecules* [2].

- Based on our experiments we confirmed first time that the pH of L-glutathione (GSH) solution has a dominant role on the interaction between $AuCl_4^-$ and GSH using

Au:GSH/15:1 molar ratio. In acidic medium (pH = 2–4) a yellow emitting (λ_{em} = 590 nm) Au(I) coordination polymer was formed. It has been observed that the fluorescence intensity showed downward tendency to pH 7.0 while between pH 8–10 this band was disappeared. However, in the alkali medium (from pH = 10) a new emission band was evolved at λ_{em} = 445 nm, which probably belonged to the few-atomic blue-emitting Au(0) NCs which was identified by XPS measurements. The different reducing properties of GSH in acidic and alkali medium was derived from the strong pH-dependent standard potential of the molecule.

- Reproductive synthesis of the fluorescent Cys-Au(I) self-assembly coordination polymer was carried out. As a new result it was shown that, the molar ratio of the reactant and the pH had dominant influence on the formation of the nanoproducts and its fluorescence properties. It has been found that, the largest emission intensity could be detectable at Cys:Au/10:1 molar ratio and the more acidic medium was preferred to the formation of the self-assembly structure, which was also supported by the decreasing of the emission peak at λ_{em} = 620 nm between pH = 1–8. The lamellar structure of the Cys-Au(I) CP was successfully confirmed by XRD.

- We successfully implemented the syntheses of 8–10 nm sized cysteinyl-tryptophan (CW)-stabilized plasmonic Au NPs (λ_{max} = 518 nm) in alkaline medium (pH = 11–12) using CW:Au/0.5:1 molar ratio. It has been observed that, increase in the dipeptide amount (CW:Au/20:1 and c_{Au} = 0.1 mM) resulted in the formation of blue-emitting (λ_{em} = 470 nm) products, which was probably identifiable as supramolecular Au(I)-complexes. The aromatic side chain of tryptophan prevented the formation of self-assembly coordination polymer structure and the pH had no dominant role on the formation of the fluorescent product.

T4. *Syntheses of the amino acid-stabilized Au systems containing aromatic-N in the side chain* [4].

- We found that, besides the ratio and the concentration of the reactants the pH was also a crucial factor during the syntheses of size-controlled *L*-tryptophan(Trp)-stabilized Au nanohybrid systems. As a result of our experiments we have verified that, in alkaline medium (pH > 11) Trp-stabilized Au colloids (λ_{max} = 530 nm) were formed using Trp:Au/0.4:1 molar ratio. In contrast, in strong acidic medium (pH < 2) the preferred process was the formation of blue-emitting (λ_{em} = 486 and 472 nm) and green-emitting (λ_{em} = 497 nm) Au NCs. We also showed that using constant Au concentration the emission is tuneable (between 472–497 nm) with increasing the amount the amino acid. The number of the atoms in the clusters

and the amino acid oligomerization, which accompanies the reduction, were confirmed by ESI- and MALDI-MS.

- The *L*-histidine was successfully applied to reduction of $AuCl_4^-$ ions in aqueous medium. It has been proved that, the presence of the fluorescence product depended on the pH of the medium after the 24 h reaction time. The maximum intensity was measurable at pH = 6.0 and using His:Au/30:1 molar ratio. During the structural analyses it has been shown that, the Au(III) ions were reduced to (+1) oxidation state, which formed $[Au_xHis_{x+1}]^+$ polynuclear complexes with helical structure.
- Because of the relatively good quantum yield (~ 4%) of the fluorescent complexes this His-containing gold system was used for fluorescent labelling of drug delivery systems. Bovine serum albumin/ibuprofen (BSA/IBU)-based nanocomposite and chitosan biopolymer-based microbeads which were synthesized previously in our group, were successfully marked confirmed by fluorescence microscopy images. During the stability test of the labelled composites it was found that, the Au(I)-complexes were further reduced by the protein in case of the BSA/IBU nanocomposite, which was supported by the formation of gold particles. The deprotonated, unbounded carboxyl groups in the $[Au_xHis_{x+1}]^+$complexes could be formed a hydrogen bond with the positive charged amino groups on the surface of the chitosan beads because the complexes stayed firmly on the surface of the microbeads during the microscopic measurements.

T5. *Synthesis and characterization of adenosine monophosphate-stabilized Au nanoparticles and nanoclusters and the detection of Fe^{3+} ions by the clusters* [3].

- It was found that, the concentrations of $AuCl_4^-$ and adenosine monophosphate (AMP) as well as their molar ratio have a great influence on the size and optical properties of the formed nanostructures. However, it has also been pointed out that, only the AMP molecules were not capable of the total reduction of $AuCl_4^-$ to Au(0) and the application of an additional mild reducing agent was also required. Therefore, the syntheses were carried out in citric acid/citrate (pH = 6.0) buffer solution. Using AMP:Au/20:1 molar ratio with 0.1 mM $AuCl_4^-$ concentration blue-emitting (λ_{em} = 480 nm) AMP-Au NCs were formed which consisted of only a few atoms. In contrast, the application of AMP:Au/1:1 molar ratio in the gold concentration range of 0.5–5 mM resulted in the formation of 10–13 nm sized AMP-Au (λ_{max} = 525 nm) colloids. The fluorescent AMP-Au NCs showed high kinetic stability under physiological

conditions (pH = 6–9 and c_{NaCl} = 0.15 M) because any significant changes of their optical properties, size and ξ-potential were not measureable. Although, in high acidic medium (pH = 1–2) a rapid aggregation of the AMP-Au NCs was observed.

- Numerous metal ions and anions were tested during the sensor investigations. During the studies, high selectivity was found only for Fe^{3+} ion, which was detected via the fluorescence quenching of the nanoclusters ($I_0/I > 3$). The minimum detectable amount of the Fe^{3+} ion was 2 μM and the dynamic range was appointed between 10–100 μM concentration.
- The Stern-Volmer constants were determined from the data of the sensor measurements based on the Stern-Volmer equation at 298, 303, 310 and 323 K. The decrease of the Stern-Volmer constant with increasing temperature supported the static quenching process between the clusters and the Fe^{3+} ions. In case of the static quenching, a non-fluorescent complex can be formed by the interaction of the fluorophore and the quencher, which was supported by the ξ-potential values. After the addition of metal ions and anions to the clusters the ξ-potential was changed only in case of Fe^{3+} ions from -35 mV to +30 mV, which was thanks the formation of the coordinative bonding between the iron(III) ions and the clusters. Using the modified Stern-Volmer plot for static quenching the association constant (K_a) of dark complex were determined, which also showed downward trend with the growing of the temperature (298, 303, 310 and 323 K). For a more detailed understanding of the mechanism the thermodynamic parameter were assigned. The quenching process was thermodynamically favourable, exothermic and enthalpy-controlled, and the intermolecular forces presumably stabilized the dark complex.

5. Publication list

Hungarian Scientific Bibliography (MTMT) identifier: 10052666

Publications related to the scientific topic of the dissertation:

[1] V. Hornok, E. Csapó, N. Varga, **D. Ungor**, D. Sebők, L. Janovák, G. Laczkó, I. Dékány: *Controlled syntheses and structural characterization of plasmonic and red-emitting gold/lysozyme nanohybrid dispersions*, Colloid Polym. Sci. 294 (2016) 49-58. doi:10.1007/s00396-015-3781-7.

IF_{2016} = 1,723

[2] E. Csapó, **D. Ungor**, Á. Juhász, G.K. Tóth, I. Dékány: Gold nanohybrid systems with tunable fluorescent feature: Interaction of cysteine and cysteine-containing peptides with gold in two- and three-dimensional systems, Colloids Surfaces A Physicochem. Eng. Asp. 511 (2016) 264-271. doi:10.1016/j.colsurfa.2016.10.003.

IF_{2016} = 2,714

[3] **D. Ungor**, E. Csapó, B. Kismárton, Á. Juhász, I. Dékány: *Nucleotide-directed syntheses of gold nanohybrid systems with structure-dependent optical features: Selective fluorescence sensing of* Fe^{3+} *ions,* Colloids Surfaces B Biointerfaces. 155 (2017) 135-141. doi:10.1016/j.colsurfb.2017.04.013.

IF_{2016} = 3,887

[4] E. Csapó, **D. Ungor**, Z. Kele, P. Baranyai, A. Deák, Á. Juhász, L. Janovák, I. Dékány: *Influence of pH and aurate/amino acid ratios on the tuneable optical features of gold nanoparticles and nanoclusters*, Colloids Surfaces A Physicochem. Eng. Asp. 532 (2017) 601-608. doi:10.1016/j.colsurfa.2017.02.047.

IF_{2016} = 2,714

Σ IF = 11, 038

Other publications:

[5] E. P. Krivan, **D. Ungor**, C. Janáky, Z. Németh, C. Visy: *Optimization of the photoactivity of conducting polymer covered ZnO nanorod composite electrodes*, J. Solid State Electrochem. 19 (2015) 37-44. doi:10.1007/s10008-014-2587-8.

IF_{2015} = 2,327

[6] Á. Deák, L. Janovák, E. Csapó, **D. Ungor**, I. Pálinkó, S. Puskás, T. Ördög, T. Ricza, I. Dékány: *Layered double oxide (LDO) particle containing photoreactive hybrid layers with tunable superhydrophobic and photocatalytic properties,* Appl. Surf. Sci. 389 (2016) 294-302. doi:10.1016/j.apsusc.2016.07.127.

IF_{2016} = 3,387

[7] Á. Juhász, E. Csapó, **D. Ungor**, G.K. Tóth, L. Vécsei, I. Dékány: *Kinetic and Thermodynamic Evaluation of Kynurenic Acid Binding to GluR1$_{270–300}$ Polypeptide by Surface Plasmon Resonance Experiments*, J. Phys. Chem. B. 120 (2016) 7844-7850. doi:10.1021/acs.jpcb.6b05682.

IF_{2016} = 3,177

[8] I. Kálomista, A. Kéri, **D. Ungor**, E. Csapó, I. Dékány, T. Prohaska, G. Galbács: *Dimensional characterization of gold nanorods by combining millisecond and microsecond temporal resolution single particle ICP-MS measurements*, J. Anal. At. Spectrom. 32 (2017) 2455-2462, doi:10.1039/C7JA00306D

IF_{2016} = 3,379

[9] A. Kéri, I. Kálomista, **D. Ungor**, Á. Bélteki, E. Csapó, I. Dékány, T. Prohaska, G. Galbács: *Determination of the structure and composition of Au-Ag bimetallic spherical nanoparticles using single particle ICP-MS measurements performed with normal and high temporal resolution*, Talanta 179 (2018) 193-199, doi: 10.1016/j.talanta.2017.10.056

IF_{2016} = 4,162

Σ IF = 16,432

$\Sigma\Sigma$ IF = 27,470

Oral and poster presentations related to the scientific topic of the dissertation:

1. E. Csapó, **D. Ungor**, Z. Kele, Á. Juhász, L. Janovák, I. Dékány: *Tunable optical features of amino acids-stabilized gold nanoparticles and nanoclusters*, 31st Conference of The European Colloid and Interface Society, Madrid, 2017 (poster)

2. **D. Ungor**, E. Csapó, Á. Juhász, I. Dékány: *Interaction of cysteine and cysteine-containing peptides with gold in two- and three-dimensional systems*, 7th International Colloids Conference, Barcelona-Sitges, 2017 (poster)

3. E. Csapó, **D. Ungor**, B. Kismárton, Á. Juhász, I. Dékány: *Nucleotide-directed syntheses of gold nanohybrid systems with structure-dependent optical features: Selective fluorescence sensing of Fe^{3+} ions*, 7th International Colloids Conference, Barcelona-Sitges, 2017 (poster)

4. E. Csapó, **D. Ungor**, Z. Kele, A. Juhász, L. Janovák, I. Dékány: *Tunable optical features of amino acids-stabilized gold nanoparticles and nanoclusters*, 5th International Conference on Bio-Sensing Technology (BITE-2017), Riva del Garda, 2017 (poster)

5. **Ungor D.**: *Biofunkcionalizált plazmonikus és fluoreszcens nemesfém nanoszerkezetek*, MTA Kolloidmunkabizottsági Ülés, Velence 2017 (oral)

6. **Ungor D.**, E. Csapó, I. Dékány: *Cisztein és cisztein-tartalmú peptidek kölcsönhatása arannyal 2- és 3-dimenziós rendszerekben*, XX. Tavaszi szél, Miskolc, 2017 (oral)

7. E. Csapó, **D. Ungor**, Á. Juhász, B. Kismárton, I. Dékány: *Biocompatible gold nanohybrid structures with tuneable plasmonic or fluorescent features: syntheses, structural characterization, possible sensoric and biolabelling applications*, Nanomed 2016, Dubai, 2016 (oral)

8. E. Csapó, **D. Ungor**, Á. Juhász, B. Kismárton, I. Dékány: *Ultra-small gold nanoclusters with tuneable fluorescent features: syntheses, structural identification and sensoric applications*, 30th Conference of the European Colloid and Interface Society, Rome, 2016 (oral)
9. **D. Ungor**, E. Csapó, B. Kismárton, Á. Juhász, I. Dékány: *Nucleotide-stabilized Au and Au/Ag nanoclusters for biosensor applications*, 8th Conference Chemistry towards Biology, Brno, 2016 (poster)

10. E. Csapó, **D. Ungor**, Á. Juhász, D. Sebők, SZ. P. Tallósy, I. Dékány: *Noble metal and protein nanohybrid systems for biomedical applications*, 6th International Colloids Conference, Berlin, 2016 (poster)

11. **Ungor D.**: *Proteinekkel-stabilizált arany nanorészecskék és nanoklaszterek jellemzése*, MTA Kolloidkémiai Munkabizottsági Ülés, Velence, 2016 (oral)

12. E. Csapó, **D. Ungor**, I. Dékány: *Ultrasmall fluorescent gold nanoclusters for biomedical applications*, 29th Conference of the European Colloid and Interface Society, Bordeaux, 2015 (poster)

13. **Ungor D.**, Csapó E., Dékány I.: *Biofunkcionalizált arany nanoklaszterek szintézise*, XIX. Tavaszi szél, Eger, 2014 (oral)

14. E Csapó, **D Ungor**, N Ábrahám, V Varga, D Sebők, Á Juhász, I Dékány: *Optical and fluorescent properties of plasmonic nano-bioconjugates*, SIWAN6, Szeged, 2014 (oral)

Other presentations:

1. Á. Juhász, E. Csapó, H. Szokolai, **D. Ungor**, I. Dékány: *Modelling and characterization of drug binding to peptide functionalized gold surfaces*, 7th International Colloids Conference, Barcelona-Sitges, 2017 (poster)

2. I. Kálomista, A. Kéri, **D. Ungor**, E. Csapó, I. Dékány, T. Prohaska, G. Galbács: *Extending the applicability of the single particle ICP-MS technique to the investigation of nanorods and nanoalloys*, Colloquium Spectroscopium Internationale XL Pisa, 2017 (poster)

3. M. Csete, A. Somogyi, A. Szenes, E. Tóth, G. Veszprémi, L. Zs. Szabó, E. Csapó, **D. Ungor**, B. Bánhegyi, T. Csendes, G. Szabó, I. Dékány: *Plasmon enhanced fluorescence bio-sensing via optimized nanorod and alloy sphere based configurations*, Quantum Nanophotonics, Benasque, 2017 (poster)

4. Á. Juhász, E. Csapó, H. Szokolai, **D. Ungor**, I. Dékány: *Kinetic and thermodynamic characterization of the interactions between kynurenic acid and human glutamate receptor fragments by surface plasmon resonance studies*, 30th Conference of the European Colloid and Interface Society, Rome, 2016 (poster)

5. I. Dékány, N. Varga, E. Csapó, V. Hornok, **D. Ungor**, Á. Juhász, D. Sebők: *Self-assembled core-shell nanoparticles for drug delivery: structural, properties and kinetic of the release process*, 6th International Congress - BioNanoMed 2015, Graz, 2015 (oral)

6. **Ungor D.**: *ZnO nanostruktúrák és vezető polimerekkel alkotott kompozitjaik előállítása, jellemzése*, XV. Eötvös Konferencia, Budapest, 2014 (oral)

7. **Ungor D.**, Lukács Zs., Peintler-Kriván E., Visy Cs.: *ZnO nanostruktúrák és vezető polimerekkel alkotott kompozitjaik előállítása, jellemzése*, XXXVI. Kémiai Előadói Napok, Szeged, 2013 (oral)

8. E. Peintler-Krivan, **D. Ungor**, Zs. Lukacs, Z. Nemeth, C. Visy: *Synthesis and Characterization of Nanostructured ZnO - Conducting Polymer Composites for Photovoltaic Application*, 64th Annual Meeting of the International Society of Electrochemistry, Santiago de Queretaro, 2013 (poster)

9. **D. A. Ungor**, A. Varga, E. Krivan, B. Endrodi, C. Jananky, C. Visy: *Synthesis, characterization and possible application of conducting polymer fiber – noble metal nanocomposites*, Third International Conference on Multifunctional, Hybrid and Nanomaterials, Sorrento, 2013 (poster)

10. **D. Ungor**, E. Peintler-Krivan, B. Endrodi, C. Janaky, C. Visy: *Synthesis and Characterization of Conducting Polymer Nanofiber Composites*, International Workshop on the Electrochemistry of Electroactive Materials, Szeged, 2012 (poster)