第 1 卷第 1 期 中国无机分析化学 Vol. 1, No. 1
2011 年 3 月 Chinese Journal of Inorganic Analytical Chemistry 32～39

纳米材料在光度分析中的应用

任翠领[1,2] 陈兴国[1,2]

(1 兰州大学化学化工学院，甘肃 兰州 730000
2 甘肃省有色金属化学与资源利用重点实验室，甘肃 兰州 730000)

摘 要 本文在对纳米材料的性质简要介绍的基础上，综述了近年来纳米金、纳米银以及纳米氧化铁等纳米材料在光度分析中的应用进展，并对其在生命分析化学中的典型应用进行了较为详细的介绍。展望了今后纳米材料在该领域的主要发展方向。共收录文献 104 篇。

关键词 纳米材料；光度法；传感器；应用

中图分类号：O657.3；TF125.2$^+$3 **文献标识码**：A **文章编号**：2095－1035(2011)01－0032－08

Application of nanomaterials in photometric analysis

REN Cuiling[1,2], CHEN Xingguo[1,2]

(1 *Chemistry and Chemical Engineering Department of Lanzhou University, Lanzhou* 730000, *China*
2 *Key Laboratory of Nonferrous Metal Chemistry and Resources Utilization of Gansu Province, Lanzhou* 730000, *China*)

Abstract On the basis of the brief introduction to the properties of nanomaterials, this paper reviews the recent application progress of gold, silver and iron oxide nanomaterials in photometric analysis. In particular, some typical applications in bioanalytical chemistry are introduced in detail. The prospective applications of nanomaterials in bioanalytical chemistry are elucidated. 104 papers are included in this review.

Keywords nanomaterials; photometric; sensor; application

1 引言

纳米材料是指尺寸在三维空间中至少有一维在纳米尺度(1～100 nm)范围内或以它们为结构单元组成的材料。纳米材料结构的特殊性使其具有量子尺寸效应、表面效应、小尺寸效应和宏观量子隧道效应等特殊效应，赋予了纳米材料特殊的光、电、磁、力、热及化学性质，使它们在环境保护、信息存储、生物医学、催化和传感等领域具有巨大的应用潜力。

近几年，纳米材料在光度分析中的应用引起了广泛的关注。纳米材料的出现和发展不仅为光度分析提供了新的探针材料，而且为光度法在分析化学特别是生命分析化学中的应用提供了新的契机。

目前已用于光度分析的纳米材料包括金、银、氧化铁、碳纳米管[1]、纳米氧化铈[2]以及石墨烯[3]等，其中应用较多的是金、银以及氧化铁纳米材料。本文将重点介绍这三种纳米材料在光度分析中的应用研究进展情况。

2 纳米材料在光度法中的应用

2.1 纳米金

纳米金具有特殊的光学性质，其胶体溶液颜色与粒径及颗粒间距有关[4-5]。粒径为 10～50 nm 的纳米金胶体溶液显红色，金纳米颗粒团聚后的聚集体呈紫色或蓝色，基于纳米金的这一性质，通过控制它们的粒径或颗粒间距并结合各种表面改性方法可

收稿日期：2010-12-03 **修回日期**：2011-1-05
基金项目：本文系国家自然科学基金项目(No. 20875040)资助。
通讯作者：陈兴国，男，教授。E-mail：chenxg@lzu.edu.cn

以设计出多种金纳米探针。

如果目标分析物或生物过程能够直接或间接引起金纳米颗粒团聚(由红变紫或变蓝)或团聚体重新分散(由紫变红),就能通过溶液颜色或吸光度值的变化进行定性或定量检测。更为重要的是,金纳米颗粒较高的摩尔吸光系数使该方法具有很高的灵敏度[6],其检测限通常为nmol/L 到μmol/L。

利用金纳米颗粒构筑光度传感平台的关键是通过所要研究的过程或分析物调节金纳米颗粒的分散或聚集状态。光度分析法中纳米金(AuNPs)的聚集机理可分为交联(颗粒间成键)和非交联(去除胶体稳定作用)两种[7]。

通过与金纳米颗粒表面受体分子有多个成键位点的交联分子,或利用金纳米颗粒表面修饰的受体分子与反受体分子之间的键合作用可以直接诱导纳米金交联聚集。利用生物识别过程(如氢键、静电作用、疏水作用、金属配体配位)能够使颗粒克服颗粒间的斥力(静电和/或空间斥力)团聚。典型的生物识别过程包括 DNA 杂交、适体-靶物质相互作用、抗体-抗原相互作用、链霉素-生物素相互作用、凝集素 - 糖相互作用和金属-配体配位作用。

基于与金纳米颗粒表面受体分子有多个成键位点的交联分子能引发金胶体聚集的现象,Mirkin 等构建了 DNA 传感器[5]。类似的方法已成功用于检测半胱氨酸[8]、限制性内切酶[9]、癌细胞[10]等物质。

因为 DNA 杂交过程可逆,所以利用 DNA 杂交对纳米颗粒聚集状态的调控也是可逆的。当温度高于其解链温度时,杂交的 DNA 双链发生变性使团聚的金纳米颗粒重新分散。基于此,Mirkin 等又建立了检测 DNA 键合分子以及 Hg^{2+} 离子的光度分析方法[11-14]。

另外,与金纳米颗粒表面具有多种成键基团的有机分子(如多糖)和基团(如巯基和胍),能通过化学作用(如 Au-S)直接与金纳米颗粒交联。Kim 基于 Hg^{2+} 与二硫赤藓糖醇能通过 S-Hg^{2+}-S 成键结合,利用二硫赤藓糖醇修饰的金纳米颗粒建立了一种可选择性检测水溶液中 Hg^{2+} 的光度分析新方法[15]。类似的方法已用于 Pb^{2+}[16]以及氨基酸[8,17]的检测。2010 年 Lu 等利用三聚氰胺和金纳米颗粒表面固定的三聚氰酸衍生物之间的氢键识别作用,建立了一种能够检测三聚氰胺的光度分析法[18]。

除了使用交联分子以外,还可以利用受体分子和互补分子(或反受体)的识别作用使金纳米颗粒自发团聚。将 DNA 和互补 DNA 修饰的金纳米颗粒混合引发金纳米颗粒聚集便属于这种情况[19]。Lu 等则利用展开的单链 DNA 能够吸附到金纳米颗粒表面使其稳定分散、双链 DNA 不具有这一性质的特点,建立了一种非标记测定 Pb^{2+} 的光度分析方法[20]。

因为金纳米颗粒团聚是一个可控的可逆过程,所以可以利用纳米金交联后的聚集体检测那些能够使聚集的纳米金重新分散的物质。Geddes 等基于刀豆球蛋白 A 能引发右旋糖酐修饰的金纳米颗粒发生团聚,葡萄糖能与刀豆蛋白 A 竞争结合使 Au 纳米颗粒团聚体重新分散,建立了一种测定葡萄糖的光度分析方法[21-22]。Mirkin 等利用 DNA 杂交制备了紫色的金纳米颗粒聚集体,然后向溶液中加入内切酶打断 DNA 双链使金纳米颗粒分散,溶液颜色由紫变红,实现了内切酶的检测[19]。Lu 等基于这种原理,建立了一系列检测 Pb^{2+}[23-24]、腺苷[25]和可卡因[26]的光度法。Shimizu 等也利用该原理成功实现了谷胱甘肽的检测[27]。

通过生化过程将交联分子转化为非交联分子或将受体分子改性为非受体分子(反之亦然),也能够使金胶体溶液的颜色发生变化,从而实现这些物质的间接检测。该方法已成功用于 β-内酰胺酶、磷酸酶和过氧化氢等物质的光度检测[28-30]。

利用颗粒间的交联聚集机理建立的纳米金光度分析方法取决于颗粒间的生物识别能力或化学作用。虽然这类方法可用于检测与颗粒间成键直接或间接相关的生物过程或物质,但是其作用过程相当慢,如利用 DNA 杂交引发金纳米颗粒聚集通常需要几个小时[31-33]。此外,当纳米颗粒聚集体被用作探针的时候,聚集体内的生物分子很难用于生物识别,限制了该方法的检测灵敏度。

非交联聚集机理是控制金纳米颗粒聚集的另一种方式。该方法是通过减弱金纳米颗粒之间的静电、空间或静电空间稳定作用使其发生聚集。向柠檬酸根分散的金纳米颗粒中加入盐,会使这些颗粒表面的电荷被屏蔽而聚集。三聚氰胺分子能将纳米金表面的柠檬酸根离子取代,同时带正电荷的三聚氰胺与纳米金表面的柠檬酸根负离子之间存在静电作用,这两种作用有效地中和了纳米金表面的负电荷使纳米金聚集,郭良洽[34]等据此实现了微量三聚氰胺的检测。类似的方法已用于金属离子、凝血酶和腺苷(ATP)等物质的测定[35-41]。该方法还可用于酶及酶反应的测定[42]。

纳米金能够有效区分其表面核酸适体与靶分子

特异性结合后的构型变化并给出相应的光学信号，因此可用作测定分子构型变化的探针[43]。Li 等[44]发现与非折叠适体连接的金纳米颗粒比与折叠适体连接的金纳米颗粒更易发生盐致聚沉。因此，通过腺苷和腺苷脱氨酶分别调节适体的折叠和非折叠状态，能方便地调控金纳米颗粒的聚沉或重新分散。该方法不仅能检测使纳米颗粒失去（静电）空间稳定性的生物过程（或分析物），还能用于研究金纳米颗粒表面（带电荷的）聚合物构型的转变对它们稳定性的影响。

除了金纳米颗粒以外，光度生物传感中所使用的金纳米探针还包括纳米棒、椭圆形纳米金等多种结构[45-51]。

纳米金在光度分析中的应用及识别机理见表 1。

表 1 纳米金在光度分析中的应用

Table 1 The applications of gold nanometerials in colorimetric analysis

	检测对象	识别机理	参考文献
交联机理	多核苷酸、DNA 结合分子、溴化乙锭、色霉素 A、限制性内切酶/甲基转移酶活性、Ag^{+}、黄曲霉毒素 B1	DNA 杂交	[5]、[9]、[11]、[13-14]、[53]、[62]、[65]
	单碱基突变、氨基酸、谷胱甘肽	Au-S 键	[52]、[17]、[27]、[64]
	腺苷、ATP、癌细胞、沙门氏菌、可卡因、血小板衍生生长因子	适体－靶物质相互作用	[10]、[25-26]、[50-51]、[54-55]、[67]
	溶菌酶、含氧负离子	静电作用	[56]、[58]
	重金属离子、过氧化氢	配位作用	[12]、[16]、[29]、[59-60]
	磷酸酶、Pb^{2+}、Cu^{2+}、核酸内切酶活性	酶解反应	[19-20]、[23-24]、[28]、[61]
	亲水性阴离子、三聚氰胺	氢键	[18]、[57]
	半胱氨酸	取代	[63]
	抗体	抗体－抗原	[48]、[66]
	多巴胺	氢键、配位	[68]
	葡萄糖	蛋白与糖的特异性识别	[21]、[22]
	链亲和素	生物素－链亲和素	[69]
非交联机理	多环芳烃、苯二胺异构体	配位、静电	[70]、[71]
	三聚氰胺、ATP 及其磷酸化反应、激酶活性、酪氨酸激酶、腺苷、NO_2^-	改变表面电荷	[34]、[37-41]、[47]
	蛋白酶	DNA 链裂解	[72]
	K^+、Ca^{2+}、蛋白质构型变化	表面修饰剂构型改变	[35]、[44]、[73-74]
	Hg^{2+}、Ag^+、Pb^{2+}、凝血酶	去除表面稳定剂	[36]、[42]、[62]、[72]
	巯基化合物	配体交换	[75]

2.2 纳米银

纳米银具有光学性质稳定、制备简单、生物相容、能与生物分子结合以及抗菌和抗血小板的性质，在生物医学中有很大的应用前景。尽管纳米银的光学性质与纳米金类似，但是纳米银在光度分析中报道比纳米金要少得多。与纳米金相比，相同粒径的纳米银具有更高的摩尔吸光系数[77]，将其用于光度传感有望提高方法的灵敏度。

与纳米金类似，纳米银在光度分析中的应用也是基于它们的分散和聚集能够使胶体溶液呈现不同的颜色特性，分散的纳米银胶体溶液呈黄色，聚集的纳米银呈淡红色或褐色。

在交联机理中，通常可以根据待分析物的性质在银纳米颗粒表面键合上能与其选择性结合的物质，利用二者的相互作用将纳米银交联使溶液颜色发生变化，实现定性或定量分析。选择性识别作用包括 DNA 杂交[76]、静电[77]、金属—配体配位[78-79]、络合[80-81]以及氢键等[82]。Han [83]等以连接有寡核苷酸的二氧化硅包裹的银纳米颗粒（$Ag@SiO_2$）作探针，建立了一种快速测定 DNA 序列的光度分析方法。Graham 等[84]首次利用寡核苷酸改性的银纳米颗粒（OSN）与靶标 DNA 之间的杂交实现了 DNA 序列的测定。Li 等利用对硝基苯胺改性的纳米银溶胶建立了一种快速测定（＜2 min）三聚氰胺的光度分析方法[85]。

若表面改性的银纳米颗粒不能直接检测分析物，可以加入一种辅助物质使二者发生作用[77]。半胱氨酸修饰的银纳米颗粒不能直接与组氨酸发生直接作用，所以 Li 等利用 Hg^{2+} 离子与半胱氨酸修饰的银纳米颗粒以及组氨酸分子结合的性质，向溶液中加入 Hg^{2+} 实现组氨酸的简单快速的检测[86]。

纳米银的非交联聚集可以通过一定的生物或化学反应将纳米银表面的分散剂改性，使其失去分散能力。Wang 等基于 ATP 能防止 AgNPs 发生盐致

聚沉、而酶催化 ATP 脱磷酸化的产物不能防止 AgNPs 发生盐致聚沉的现象，建立了一种灵敏、选择性、简单、无标记的测定酶反应的光度分析方法[87]。纳米银的非交联聚集也可以通过改变纳米颗粒的表面电荷或表面物质的构型实现。Yang 等据此建立了一种能选择性测定 Hg (II)的灵敏的光度方法[88]。

除了上面介绍的银纳米颗粒以外，用于光度生物传感的纳米银还包括银纳米盘、三角形纳米银等[89-90]。纳米银在光度分析中的研究应用及其识别作用类型见表 2。

表 2　纳米银在光度分析中的应用

Table 2　The applications of silver nanometerials in colorimetric analysis

	检测对象	识别机理	参考文献
交联机理	DNA	DNA 杂交	[76]、[83-84]
	组氨酸以及组氨酸标记的蛋白	静电作用	[77]
	Cr、Co、芳香族化合物	配位作用	[78-79]、[93]
	水胺硫磷	络合作用	[80]
	三聚氰胺、菊酯类农药	氢键	[85]、[91]
	组氨酸、色胺酸	络合作用/配位作用	[81]、[86]、[92]
	色氨酸	π－π 作用和氢键	[82]
	半胱氨酸	Ag－S 成键	[90]
非交联机理	磷酸酶和蛋白激酶	酶反应	[87]
	Hg^{2+}、细胞色素 c 构型变化	稳定剂构型变化	[88-89]
	蛋白质	改变表面电荷	[94]

2.3　纳米氧化铁

Yan 等首次报道了氧化铁纳米颗粒具有类似过氧化物酶的催化活性，发现磁性氧化铁纳米粒子能够催化 H_2O_2 氧化 3，3′，5，5′-四甲基联苯胺(TMB)、重氮胺基苯 (DAB)和邻苯二胺 (OPD)的反应，并且产物分别为蓝色、棕色和橙色[95]。利用这些过氧化物酶底物的显色反应对目标物质进行检测是氧化铁纳米颗粒在光度分析研究中应用的主要原理。基于此，Wang 等建立了一种检测 H_2O_2 的光度法。作者将 Fe_3O_4 MNPs 用于催化 H_2O_2 与 2，2-连氮-双(3-乙基苯并噻-6-磺酸)磷酸氢二铵盐(ABTS)的氧化还原反应，通过观察溶液的颜色变化实现了 H_2O_2 的检测。作者还基于葡萄糖酶催化葡萄糖氧化可产生 H_2O_2 的现象，利用上述方法间接测定了葡萄糖[96]。Chen 等[97]利用四氧化三铁纳米颗粒的这种性质，建立了一种简单快速检测乳制品中三聚氰胺的光度法，其检测限为 2.0 μmol/L，回收率为 98%～115%。该方法用眼睛就能确定乳制品中三聚氰胺是否超标。杨秀荣等利用 TMB 的变色反应建立了测定凝血酶的光度法[98]。纳米铁在光度分析中的应用见表 3。

表 3　纳米氧化铁在光度分析中的应用

Table 3　The applications of iron oxide nanometerials in colorimetric analysis

对象	显色试剂	参考文献
H_2O_2	TMB	[99]、[100]
H_2O_2	二乙基苯二胺硫酸酯(DPD)	[101]
H_2O_2	TMB、DAB 和 OPD	[95]
H_2O_2、葡萄糖	ABTS	[96]
葡萄糖	ABTS	[102-103]
三聚氰胺	ABTS	[97]
凝血酶	TMB	[98]、[104]

3　展望

纳米金、银以及氧化铁在光度法中的研究已经取得了一定进展，在生物光度分析中发挥着重要作用。随着科技的进一步发展，纳米材料在生物光度传感领域的应用必将得到进一步扩展。探索和研究纳米材料的新识别原理，设计性质优异的可用于光度分析的新型纳米探针，建立简单、快速、高灵敏度、高选择性、适合于复杂生物体系中的光度分析方法是该领域今后发展的主要方向。

参考文献

[1] Lee A C, Ye J S, Tan S N, et al. Carbon nanotube-based labels for highly sensitive colorimetric and aggregation-based visual detection of nucleic acids[J]. Nanotechnology, 2007, 18: 455102.

[2] Asati A, Santra S, Kaittanis C, et al. Oxidase Activity of Polymer-Coated Cerium Oxide Nanoparticles[J]. Angew. Chem. Int. Ed. Engl., 2009, 48(13): 2308-2312.

[3] Song Y, Qu K, Zhao C, et al. Graphene Oxide: Intrinsic Peroxidase Catalytic Activity and Its Application to Glucose Detection[J]. Adv. Mater., 2010, 22: 2206-2210.

[4] Haes A J, Van Duyne R P. Preliminary studies and potential applications of localized surface plasmon resonance spectroscopy in medical diagnostics[J]. Expert Rev. Mol. Diagn. 2004, 4: 527-537.

[5] Elghanian R, Storhoff J J, Mucic R C, et al. Selective Colorimetric Detection of Polynucleotides Based on the

Distance-Dependent Optical Properties of Gold Nanoparticles[J]. Science, 1997, 277: 1078-1081.

[6] Ghosh S K, Pal T. Interparticle Coupling Effect on the Surface Plasmon Resonance of Gold Nanoparticles: From Theory to Applications[J]. Chem. Rev., 2007, 107: 4797-4862.

[7] Zhao W, Brook M A, Li Y. Design of Gold Nanoparticle-Based Colorimetric Biosensing Assays[J]. ChemBioChem., 2008, 9: 2363-2371.

[8] Lee J S, Ulmann P A, Han M S, et al. A DNA Gold Nanoparticle-Based Colorimetric Competition Assay for the Detection of Cysteine[J]. Nano Lett., 2008, 8: 529-533.

[9] Song G, Chen C, Ren J, et al. A Simple, Universal Colorimetric Assay for Endonuclease/Methyltransferase Activity and Inhibition Based on an Enzyme-Responsive Nanoparticle System[J]. ACS Nano, 2009, 3(5): 1183-1189.

[10] Medley C D, Smith J E, Tang Z, et al. Gold Nanoparticle-Based Colorimetric Assay for the Direct Detection of Cancerous Cells[J]. Anal. Chem., 2008, 80: 1067-1072.

[11] Han M, Lytton-Jean A K R, Mirkin C A. A Gold Nanoparticle Based Approach for Screening Triplex DNA Binders[J]. J. Am. Chem. Soc., 2006, 128: 4954-4955.

[12] Lee J, Han M, Mirkin C A. Colorimetric Detection of Mercuric Ion (Hg^{2+}) in Aqueous Media using DNA-Functionalized Gold Nanoparticles[J]. Angew. Chem. Int. Ed. Engl., 2007, 46: 4093-4096.

[13] Han M S, Lytton-Jean A K R, Oh B K, et al. Colorimetric Screening of DNA-Binding Molecules with Gold Nanoparticle Probes[J]. Angew. Chem. Int. Ed. Engl., 2006, 45: 1807-1810.

[14] Hurst S J, Han M, Lytton-Jean A K R, et al. Screening the Sequence Selectivity of DNA-Binding Molecules Using a Gold Nanoparticle-Based Colorimetric Approach[J]. Anal. Chem., 2007, 79: 7201-7205.

[15] Kim Y R, Mahajan R K, Kim J S, et al. Highly Sensitive Gold Nanoparticle-Based Colorimetric Sensing of Mercury(II) through Simple Ligand Exchange Reaction in Aqueous Media[J]. ACS Applied materials and surfaces, 2010, 2: 292-295.

[16] Chai F, Wang C, Wang T, et al. Colorimetric Detection of Pb^{2+} Using Glutathione Functionalized Gold Nanoparticles[J]. ACS Applied materials and surfaces, 2010, 2(5): 1466-1470.

[17] Zhang F X, Han L, Israel L B, et al. Colorimetric detection of thiol-containing amino acids using gold nanoparticles[J]. Analyst, 2002, 127: 462-465.

[18] Ai K, Liu Y, Lu L. Hydrogen-Bonding Recognition-Induced Color Change of Gold Nanoparticles for Visual Detection of Melamine in Raw Milk and Infant Formula [J]. J. Am. Chem. Soc., 2009, 131 (27): 9496-9497.

[19] Xu X, Han M, Mirkin C A. A Gold-Nanoparticle-Based Real-Time Colorimetric Screening Method for Endonuclease Activity and Inhibition [J]. Angew. Chem. Int. Ed. Engl., 2007, 46: 3468-3470.

[20] Wang Z, Lee J H, Lu Y. Label-Free Colorimetric Detection of Lead Ions with a Nanomolar Detection Limit and Tunable Dynamic Range by using Gold Nanoparticles and DNAzyme[J]. Adv. Mater., 2008, 20: 3263-3267.

[21] Aslan K, Lakowicz J R, Geddes C D. Plasmonic tunable glucose sensing based on the dissociation of Con A-aggregated dextran-coated gold colloids [J]. Anal. Chim. Acta, 2004, 517: 139-144.

[22] Aslan K, Lakowicz J R, Geddes C D. Nanogold-plasmon-resonance-based glucose sensing[J]. Anal. Bio. Chem., 2004, 330: 145-155.

[23] Liu J, Lu Y. Accelerated Color Change of Gold Nanoparticles Assembled by DNAzymes for Simple and Fast Colorimetric Pb^{2+} Detection[J]. J. Am. Chem. Soc., 2004, 126: 12298-12305.

[24] Liu J, Lu Y. A Colorimetric Lead Biosensor Using DNAzyme-Directed Assembly of Gold Nanoparticles [J]. J. Am. Chem. Soc., 2003, 125: 6642-6643.

[25] Liu J, Lu Y. Adenosine-Dependent Assembly of Aptazyme-Functionalized Gold Nanoparticles and Its Application as a Colorimetric Biosensor [J]. Anal. Chem., 2004, 76(6): 1627-1632.

[26] Liu J, Lu Y. Fast Colorimetric Sensing of Adenosine and Cocaine Based on a General Sensor Design Involving Aptamers and Nanoparticles[J]. Angew. Chem. Int. Ed. Engl., 2005, 45(1): 90-94.

[27] Uehara N, Ookubo K, Shimizu T. Colorimetric Assay of Glutathione Based on the Spontaneous Disassembly of Aggregated Gold Nanocomposites Conjugated with Water-Soluble Polymer[J]. Langmuir, 2010, 26(9): 6818-6825.

[28] Choi Y, Ho N, Tung C. Sensing Phosphatase Activity by Using Gold Nanoparticles[J]. Angew. Chem. Int. Ed. Engl., 2007, 46: 707-709.

[29] Wu Z, Zhang S, Guo M, et al. Homogeneous, unmodified gold nanoparticle-based colorimetric assay of hydrogen peroxide[J]. Anal. Chim. Acta, 2007, 584:

122-128.

[30] Gates A T, Fakayode S O, Lowry M, et al. Gold Nanoparticle Sensor for Homocysteine Thiolactone-Induced Protein Modification[J]. Langmuir, 2008, 24: 4107-4113.

[31] Liu J, Lu Y. Stimuli-responsive disassembly of nanoparticle aggregates for light-up colorimetric sensing[J]. J. Am. Chem. Soc., 2005, 127: 12677-12683.

[32] Liu J, Lu Y. Design of asymmetric DNAzymes for dynamic control of nanoparticle aggregation states in response to chemical stimuli[J]. Org. Biomol. Chem., 2006, 4: 3435-3441.

[33] Liu J, Lu Y. Smart Nanomaterials Responsive to Multiple Chemical Stimuli with Controllable Cooperativity [J]. Adv. Mater., 2006, 18: 1667-1671.

[34] 钟坚海，吴金梅，郭良洽，等. 纳米金比色法快速检测三聚氰胺的研究[J]. 分析化学，2009，37(增刊)：C081.

[35] Wang L, Liu X, Hu X, et al. Unmodified gold nanoparticles as a colorimetric probe for potassium DNA aptamers[J]. Chem. Commun., 2006, 3780-3782.

[36] Wei H, Li B, Li J, et al. Simple and sensitive aptamer-based colorimetric sensing of protein using unmodified gold nanoparticle probes[J]. Chem. Commun., 2007: 3735-3737.

[37] Wang J, Wang L, Liu X, et al. A Gold Nanoparticle-Based Aptamer Target Binding Readout for ATP Assay [J]. Adv. Mater., 2007, 19: 3943-3946.

[38] Oishi J, Asami Y, Mori T, et al. Measurement of Homogeneous Kinase Activity for Cell Lysates Based on the Aggregation of Gold Nanoparticles[J]. ChemBioChem., 2007, 8: 875-879.

[39] Oishi J, Han X, Kang J, et al. High-throughput colorimetric detection of tyrosine kinase inhibitors based on the aggregation of gold nanoparticles[J]. Anal. Biochem., 2008, 373: 161-163.

[40] Zhao W, Chiuman W, Brook M A, et al. Simple and Rapid Colorimetric Biosensors Based on DNA Aptamer and Noncrosslinking Gold Nanoparticle Aggregation [J]. ChemBioChem., 2007, 8: 727-731.

[41] Lin C Y, Yu C J, Lin Y H, et al. Colorimetric Sensing of Silver (I) and Mercury (II) Ions Based on an Assembly of Tween 20-Stabilized Gold Nanoparticles[J]. Anal. Chem., 2010, 82 (16): 6830-6837.

[42] Zhao W, Chiuman W, Lam J, et al. Simple and rapid colorimetric enzyme sensing assays using noncrosslinking gold nanoparticle aggregation[J]. Chem. Commun., 2007, 3729-3731.

[43] 刘刚，潘敦，刘丽，等. 纳米金与生物分子的相互作用及生物传感检测[J]. 纳米材料与应用，2009，6 (3)：6-9.

[44] Zhao W, Chiuman W, Lam J, et al. DNA Aptamer Folding on Gold Nanoparticles: From Colloid Chemistry to Biosensors[J]. J. Am. Chem. Soc., 2008, 130: 3610-3618.

[45] Pan B, Ao L, Gao F, et al. End-to-end self-assembly and colorimetric characterization of gold nanorods and nanospheres via oligonucleotide hybridization [J]. Nanotechnology, 2005, 16: 1776-1780.

[46] Huang H, Liu X, Hu T, et al. Ultra-sensitive detection of cysteine by gold nanorod assembly[J]. Biosens. Bioelectron., 2010, 25: 2078-2083.

[47] Xiao N, Yu C. Rapid-Response and Highly Sensitive Noncross-Linking Colorimetric Nitrite Sensor Using 4-Aminothiophenol Modified Gold Nanorods[J]. Anal. Chem., 2010, 82 (9): 3659-3663.

[48] Wang C, Chen Y, Wang T, et al. Biorecognition-Driven Self-Assembly of Gold Nanorods: A Rapid and Sensitive Approach toward Antibody Sensing[J]. Chem. Mater., 2007, 19 (24): 5809-5811.

[49] Sudeep P K, Shibu Joseph S T, George Thomas K. Selective Detection of Cysteine and Glutathione Using Gold Nanorods[J]. J. Am. Chem. Soc., 2005, 127 (18): 6516-6517.

[50] Lu W, Arumugam S R, Senapati D, et al. Multifunctional Oval-Shaped Gold-Nanoparticle-Based Selective Detection of Breast Cancer Cells Using Simple Colorimetric and Highly Sensitive Two-Photon Scattering Assay[J]. ACS NANO, 2010, 4(3): 1739-1749.

[51] Wang S, Singh A K, Senapati D, et al. Rapid Colorimetric Identification and Targeted Photothermal Lysis of Salmonella Bacteria by Using Bioconjugated Oval-Shaped Gold Nanoparticles[J]. Chem-Eur J., 2010, 16(19): 5600-5606.

[52] 莫志宏，郭昆鹏，杨小超. 采用纳米金和双链探针比色检测单碱基突变[J]. 分析化学研究简报，2008，36：518-520.

[53] Storhoff J J, Elghanian R, Mucic R C, et al. One-Pot Colorimetric Differentiation of Polynucleotides with Single Base Imperfections Using Gold Nanoparticle Probes[J]. J. Am. Chem. Soc., 1998, 120: 1959-1964.

[54] Liu J, Lu Y. Preparation of aptamer-linked gold nanoparticle purple aggregates for colorimetric sensing of analytes[J]. Nat. Protoc., 2006, 1(1): 246-252.

[55] Chen S J, Huang Y F, Huang C C, et al. Colorimetric determination of urinary adenosine using aptamer-modi-

fied gold nanoparticles [J]. Biosens. Bioelectron, 2008, 23: 1749-1753.

[56] Chen Y M, Yu C J, Cheng T L, et al. Colorimetric Detection of Lysozyme Based on Electrostatic Interaction with Human Serum Albumin-Modified Gold Nanoparticles[J]. Langmuir, 2008, 24: 3654-3660.

[57] Kado S, Furui A, Akiyama Y, et al. Application of Gold Nanoparticles to Spectrophotometric Sensing of Hydrophilic Anions Based on Molecular, Recognition by Urea Derivative[J]. Anal. Sci., 2009, 25: 261-265.

[58] Kubo Y, Uchida S, Kemmochi Y, et al. Isothiouronium-modified gold nanoparticles capable of colorimetric sensing of oxoanions in aqueous MeOH solution[J]. Tetrahedron Lett., 2005, 46(25): 4369-4372.

[59] Kim Y, Johnson R C, Hupp J T. Gold Nanoparticle-Based Sensing of "Spectroscopically Silent" Heavy Metal Ions[J]. Nano Lett., 2001, 1(4): 165-167.

[60] Ma M, Wang J, Zheng X. Enhancement of the colorimetric sensitivity of gold nanoparticles with triethanolamine to minimize interparticle repulsion[J]. Microchim. Acta, DOI 10.1007/s00604-010-0480-4.

[61] Liu J, Lu Y. Colorimetric Cu^{2+} detection with a ligation DNAzyme and nanoparticles [J]. Chem. Commun., 2007, 4872-4874.

[62] Li B, Du Y, Dong S. DNA based gold nanoparticles colorimetric sensors for sensitive and selective detection of Ag(I) ions[J]. Anal. Chim. Acta., 2009, 644: 78-82.

[63] Wei X, Qi L, Tan J, et al. A colorimetric sensor for determination of cysteine by carboxymethyl cellulose-functionalized gold nanoparticles[J]. Anal. Chim. Acta, 2010, 671: 80-84.

[64] 许文杰，李正平，段新瑞，等. 金纳米粒子与谷胱甘肽相互作用及其分析应用[J]. 河北大学学报:自然科学版, 2007, 27(3): 265-269.

[65] Liao J Y, Li H. Lateral flow immunodipstick for visual detection of aflatoxin B1 in food using immuno-nanoparticles composed of a silver core and a gold shell[J]. Microchim. Acta, 2010, 171: 289-295.

[66] Thanh N T K, Rosenzweig Z. Development of an Aggregation-Based Immunoassay for Anti-Protein A Using Gold Nanoparticles[J]. Anal. Chem., 2002, 74: 1624-1628.

[67] Huang C C, Huang Y F, Cao Z, et al. Aptamer-Modified Gold Nanoparticles for Colorimetric Determination of Platelet-Derived Growth Factors and Their Receptors[J]. Anal. Chem., 2005, 77: 5735-5741.

[68] Zhang Y, Li B, Chen X. Simple and sensitive detection of dopamine in the presence of high concentration of ascorbic acid using gold nanoparticles as colorimetric probes[J]. Microchim. Acta, 2010, 168: 107-113.

[69] Nath N, Chilkoti A. A Colorimetric Gold Nanoparticle Sensor to Interrogate Biomolecular Interactions in Real Time on a Surface[J]. Anal. Chem., 2002, 74: 504-509.

[70] 李海兵，曾丽霖，熊得军，等. 磺化杯[6]芳烃修饰的金纳米粒的合成及其对多环芳烃的比色检测[J]. 高等学校化学学报, 2008, 29(9): 1736-1739.

[71] Han C, Zeng L, Li H, et al. Colorimetric detection of pollutant aromatic amines isomers with p-sulfonatocalix[6]arene-modified gold nanoparticles[J]. Sensor Actuat B-Chem, 2009, 137: 704-709.

[72] Zhao W, Lam J C F, Chiuman W, et al. Enzymatic Cleavage of Nucleic Acids on Gold Nanoparticles: A Generic Platform for Facile Colorimetric Biosensors [J]. Small, 2008, 4: 810-816.

[73] Kim S, Park J W, Kim D, et al. Bioinspired Colorimetric Detection of Calcium(II) Ions in Serum Using Calsequestrin-Functionalized Gold Nanoparticles [J]. Angew. Chem. Int. Ed. Engl., 2001, 40: 2257-2261.

[74] Chah S, Hammond M R, Zare R N. Gold Nanoparticles as a Colorimetric Sensor for Protein Conformational Changes[J]. Chem. Biol., 2005, 12: 323-328.

[75] Chen S J, Chang H T. Nile Red-Adsorbed Gold Nanoparticles for Selective Determination of Thiols Based on Energy Transfer and Aggregation[J]. Anal. Chem., 2004, 76: 3727-3734.

[76] Thompson D G, Enright A, Faulds K, et al. Ultrasensitive DNA Detection Using Oligonucleotide? Silver Nanoparticle Conjugates[J]. Anal. Chem., 2008, 80 (8): 2805-2810.

[77] Bae D R, Han W S, Lim J M, et al. Lysine-Functionalized Silver Nanoparticles for Visual Detection and Separation of Histidine and Histidine-Tagged Proteins[J]. Langmuir, 2010, 26(3): 2181-2185.

[78] Wu T, Liu C, Tan K J, et al. Highly selective light scattering imaging of chromium (III) in living cells with silver nanoparticles[J]. Anal. Bioanal. Chem., 2010, 397: 1273-1279.

[79] Yao Y, Tian D, Li H. Cooperative Binding of Bifunctionalized and Click-Synthesized Silver Nanoparticles for Colorimetric Co^{2+} Sensing[J]. ACS Applied materials and surfaces, 2010, 2: 684-690.

[80] Xiong D, Li H. Colorimetric detection of pesticides based on calixarene modified silver nanoparticles in wa-

ter[J]. Nanotechnology, 2008, 19: 465502 (6pp).

[81] Xiong D, Chen M, Li H. Synthesis of para-sulfonatocalix[4]arene-modified silver nanoparticles as colorimetric histidine probes[J]. Chem. Commun., 2008, 880-882.

[82] Li H, Li F, Han C, et al. Highly sensitive and selective tryptophan colorimetric sensor based on 4,4-bipyridine-functionalized silver nanoparticles[J]. Sensor Actuat B-Chem., 2010, 145: 194-199.

[83] Liu S, Zhang Z, Han M. Gram-Scale Synthesis and Biofunctionalization of Silica-Coated Silver Nanoparticles for Fast Colorimetric DNA Detection[J]. Anal. Chem., 2005, 77 (8): 2595-2600.

[84] Thompson D G, Enright A, Faulds K, et al. Ultrasensitive DNA Detection Using Oligonucleotide Silver Nanoparticle Conjugates[J]. Anal. Chem., 2008, 80 (8): 2805-2810.

[85] Han C, Li H. Visual detection of melamine in infant formula at 0.1 ppm level based on silver Nanoparticles [J]. Analyst, 2010, 135: 583-588.

[86] Li H, Bian Y. Selective colorimetric sensing of histidine in aqueous solutions using cysteine modified silver nanoparticles in the presence of Hg^{2+} [J]. Nanotechnology, 2009, 20: 145502.

[87] Wei H, Chen C, Han B, et al. Enzyme Colorimetric Assay Using Unmodified Silver Nanoparticles[J]. Anal. Chem., 2008, 80: 7051-7055.

[88] Wang Y, Yang F, Yang X. Colorimetric Detection of Mercury(II) Ion Using Unmodified Silver Nanoparticles and Mercury-Specific Oligonucleotides[J]. ACS Applied materials and surfaces, 2010, 2: 339-342.

[89] Park J, Yoon D Y, Kim Y. Applications of silver nanoplates as colorimetric indicators of pH-induced conformational changes in cytochrome c[J]. Korean J. Chem. Eng., 2009, 26(1): 258-260.

[90] Wu T, Li Y F, Huang C Z. Selectively colorimetric detection of cysteine with triangular silver nanoprisms [J]. Chinese Chem. Lett., 2009, 20: 611-614.

[91] 李玉玲，李大鹏，田德美，等. 二氧化硅包裹的银纳米粒子对菊酯类农药的比色检测[J]. 分析化学，2009, 37(增刊): C017.

[92] 李海兵，胡春秀，韩翠平，等. β-环糊精修饰的银量子点合成及其对色氨酸的比色手性识别[J]. 中国科学 B辑:化学，2009, 39 (7): 629-633.

[93] Chen X, Parker S G, Zou G, et al. β-Cyclodextrin-Functionalized Silver Nanoparticles for the Naked Eye Detection of Aromatic Isomers[J]. ACS Nano, 2010, 4(11): 6387-6394.

[94] Shrivastava S, Dash D. Label-free colorimetric estimation of proteins using nanoparticles of silver[J]. Nano-Micro Lett., 2010, 2: 164-168.

[95] Gao L, Zhuang J, Nie L, et al. Intrinsic peroxidase-like activity of ferromagnetic nanoparticles[J]. Nat. Nanotechnol., 2007, 577-583.

[96] Wei H, Wang E. Fe_3O_4 Magnetic Nanoparticles as Peroxidase Mimetics and Their Applications in H_2O_2 and Glucose Detection[J]. Anal. Chem., 2008, 80: 2250-2254.

[97] Ding N, Yan N, Ren C, et al. Colorimetric Determination of Melamine in Dairy Products by Fe3O4 Magnetic Nanoparticles-H_2O_2－ABTS Detection System[J]. Anal. Chem., 2010, 82: 5897-5899.

[98] 张占霞，杨秀荣. 磁性纳米粒子催化显色反应对凝血酶的检测[J]. 分析化学，2009, 37(增刊): C023.

[99] Nath S, Kaittanis C, Ramachandran V, et al. Synthesis, magnetic characterization and sensing applications of novel dextran-coated iron oxide nanorods[J]. Chem. Mater., 2009, 21(8): 1761-1767.

[100] Zhuang J, Zhang J, Gao L, et al. A novel application of iron oxide nanoparticles for detection of hydrogen peroxide in acid rain[J]. Mater. Lett., 2008, 62: 3972-3974.

[101] Chang Q, Deng K, Zhu L, et al. Determination of hydrogen peroxide with the aid of peroxidase-like Fe_3O_4 magnetic nanoparticles as the catalyst[J]. Microchim Acta, 2009, 165: 299-305.

[102] Yu C J, Lin C Y, Liu C H, et al. Synthesis of poly (diallyldimethylammonium chloride)-coated Fe_3O_4 nanoparticles for colorimetric sensing of glucose and selective extraction of thiol[J]. Biosens. Bioelectron., 2010, 26: 913-917.

[103] Yu F, Huang Y, Cole A J, et al. The artificial peroxidase activity of magnetic iron oxide nanoparticles and its application to glucose detection[J]. Biomaterials, 2009, 30: 4716-4722.

[104] Zhang Z, Wang Z, Wang X, et al. Magnetic nanoparticle-linked colorimetric aptasensor for the detection of thrombin[J]. Sensor Actuat B-Chem., 2010, 147: 428-433.