Microchim Acta (2017) 184:1899–1914
DOI 10.1007/s00604-017-2318-9

REVIEW ARTICLE

The quenching of the fluorescence of carbon dots: A review on mechanisms and applications

Fanlin Zu[1] · Fanyong Yan[1] · Zhangjun Bai[1] · Jinxia Xu[1] · Yinyin Wang[1] · Yicun Huang[1] · Xuguang Zhou[1]

Received: 4 March 2017 / Accepted: 27 April 2017 / Published online: 30 May 2017

Abstract Carbon dots (CDs) possess unique optical properties such as tunable photoluminescence (PL) and excitation dependent multicolor emission. The quenching and recovery of the fluorescence of CDs can be utilized for detecting analytes. The PL mechanisms of CDs have been discussed in previous articles, but the quenching mechanisms of CDs have not been summarized so far. Quenching mechanisms include static quenching, dynamic quenching, Förster resonance energy transfer (FRET), photoinduced electron transfer (PET), surface energy transfer (SET), Dexter energy transfer (DET) and inner filter effect (IFE). Following an introduction, the review (with 88 refs.) first summarizes the various kinds of quenching mechanisms of CDs (including static quenching, dynamic quenching, FRET, PET and IFE), the principles of these quenching mechanisms, and the methods of distinguishing these quenching mechanisms. This is followed by an overview on applications of the various quenching mechanisms in detection and imaging.

Keywords Quenching mechanisms · Static quenching · Dynamic quenching · Förster resonance energy transfer · Photoinduced electron transfer · Surface energy transfer · Dexter energy transfer · Inner filter effect

✉ Fanyong Yan
yanfanyong@tjpu.edu.cn

✉ Xuguang Zhou
xaodayin@sohu.com

[1] State Key Laboratory of Hollow Fiber Membrane Materials and Processes, Key Lab of Fiber Modification & Functional Fiber of Tianjin, Tianjin Polytechnic University, Tianjin 300387, People's Republic of China

Introduction

Carbon dots (CDs) are a kind of quasi-spherical particles with a diameter of less than 10 nm [1–4]. CDs possess unique optical properties such as tunable photoluminescence (PL) and excitation dependent multicolor emission [5–7]. These properties result from the quantum confinement effect or conjugated π-domains [8–10]. Compared with the organic probes and the quantum dots (QDs) of the CdSe type, the CDs had unique merits such as excellent water dispersibility, good photostability, biocompatibility, cell permeability and low toxicity [11–15]. CDs have been applied to detecting analytes, bioimaging and drug delivery [16, 17]. These applications were based on the principle that the interactions between analytes and CDs either decrease the fluorescence by quenching, or increase fluorescence by suppressing the quenching effect. Quenching mechanisms of CDs include static quenching, dynamic quenching, energy transfer, photoinduced electron transfer (PET) and inner filter effect (IFE) [18]. The energy transfer is divided into Förster resonance energy transfer (FRET), Dexter energy transfer (DET) and Surface energy transfer (SET). Static quenching occurs when a nonfluorescent ground-state complex is formed through the interaction between CDs and quencher. Dynamic quenching can be explained as an effect where the excited state returns to the ground state by the collision between the quencher and CDs due to energy transfer or charge transfer [19]. The term FRET is the acronym for Foerster resonance energy transfer, named after a German scientist who discovered it in 1948. In FRET, photonic energy of a first fluorophore (the donor) is acquired by a second fluorophore (the "acceptor"), and then emitted by the second fluorophore. DET is an effect which is based on electron transfer, not

photon transfer and therefore requires a match between the redox potentials of donor and acceptor. SET is a rather "new" process. It is most often observed with (metal) nanoparticles and involves a metallic surface (such as on gold NPs) and a molecular (organic) dipole. The IFE occurs when the absorption spectrum of the "quencher" in the detection system overlaps the excitation or emission spectra of CDs. The IFE mechanism of CDs is different from static and dynamic quenching mechanism of CDs. It does not require to modify the CDs. In this work, we summarize that the features of static quenching, dynamic quenching, FRET, PET, DET, SET and IFE, the methods of distinguishing these quenching mechanisms in CDs, and the applications involving such quenching mechanisms.

Quenching mechanisms of CDs

Static quenching mechanism of CDs

Static quenching occurs when a nonfluorescent ground-state complex is formed through the interaction between CDs and quencher. The complex immediately returns to the ground state without emission of a photon when the complex absorbs light [19]. For static quenching (a) $\tau_0/\tau = 1$; (b) The formation

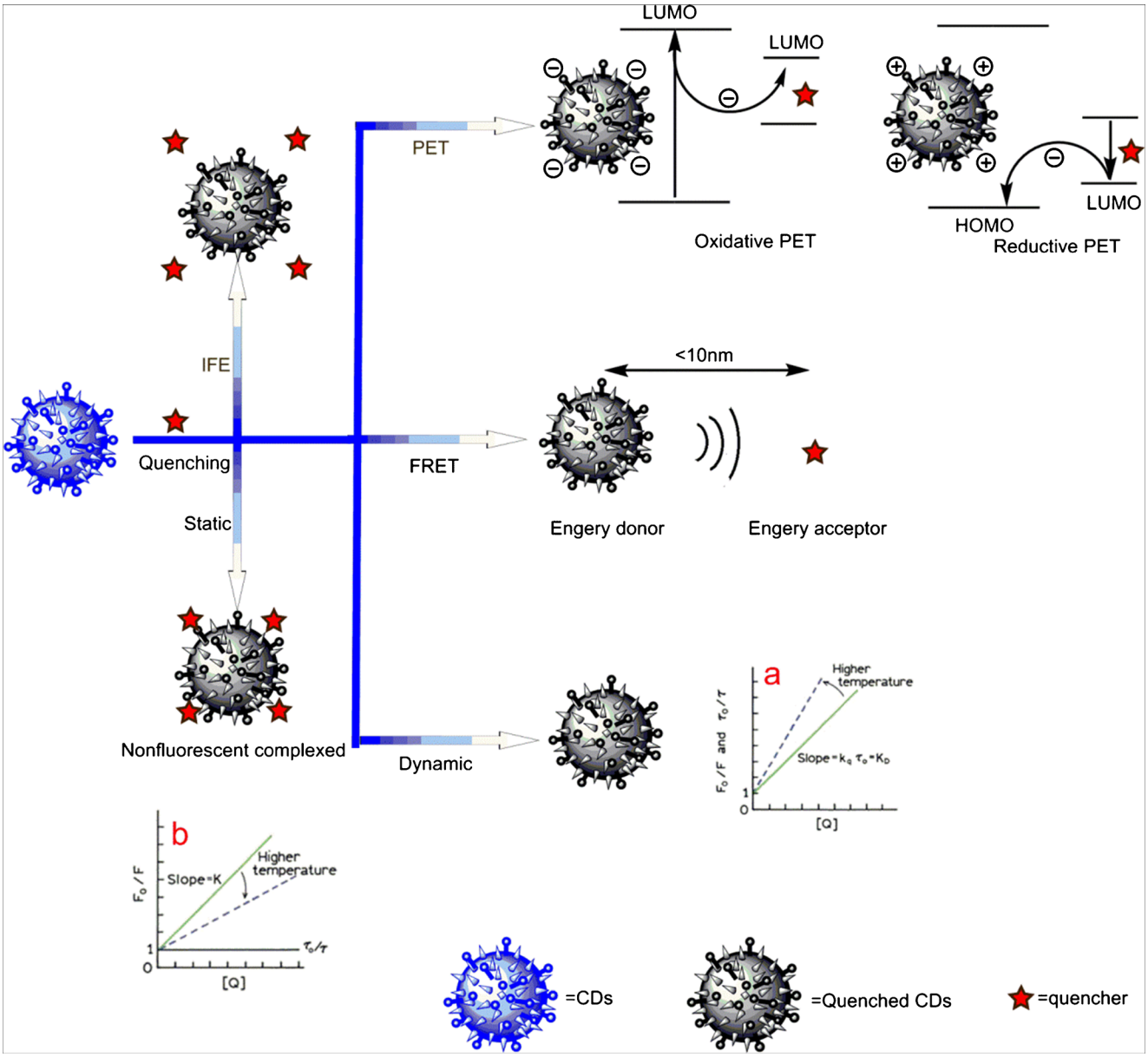

Fig. 1 Quenching mechanisms of fluorescent CDs which is used in the process of detecting analytes

Table 1 The most characteristic differences of static quenching, dynamic quenching, FRET, PET, DET, SET and IFE

	Static quenching	Dynamic quenching	FRET	PET	DET	SET	IFE
Distance	temperature dependent	viscosity dependent	1–10 nm; efficiency decrease with 6th power of distance; lifetime of donor is reduced	not critical	<1.5 nm	>15 nm; efficiency depends on 4th power of distance	>20 nm
Mechanisms	it occurs when the molecules form a complex in the ground state	particles diffuse and collide to cause excited state deactivation, usually by spin exchange	dipole interaction (no emission of light involved)	between the CDs and the quencher occurred the electron transfer, formed the cation radical and the anion radical respectively	electron transfer	dipole interaction (similar to FRET)	radiative re-absorption; light is first emitted and then re-absorbed by the second species
Orientation	not critical	not critical	requires good orientation of (excited state) dipoles	not critical	not critical	not known	not critical
Redox potential	not critical	not critical	not important	redox potentials must be high enough to allow for electron transfer	redox potentials must be high enough to allow for electron transfer	not critical	not critical
Spectral overlap needed	not required	not required	mandatory	not required	not required	not required	required

of the ground-state complex can result in the change of the absorption spectrum of the CDs; (c) A rise of temperature can cause the decline of the stability of the ground-state complex, so reduces the effect of static quenching [18–20], as showed in Fig. 1(b).

There are the CDs which can be quenched by hemoglobin (HGB) [21], this process can verify the theory of static quenching mechanism well. The CDs can react with HGB to form the ground state complex, which led to the fluorescence quenching of CDs. In order to prove that the quenching mechanism of CDs was static quenching, the average fluorescence lifetime of CDs was measured to be 6.46 ns. When HGB was added into the solution of CDs, the average fluorescence lifetime of CDs was measured to be 6.51 ns. The average fluorescence lifetime of CDs was almost unchanged in the absence or presence of HGB, this phenomenon met (a). UV–vis absorption spectra of CDs, HGB, and CDs-HGB system were measured. The absorbance peak of HGB was at 403 nm, The CDs-HGB system also showed the absorbance peak at 403 nm, it implied the formation of CDs-HGB complex, it met (b). The quenching mechanism of CDs was static quenching.

Dynamic quenching mechanism of CDs

Dynamic quenching can be explained that the excited state of CDs return to the ground state by the collision between the quencher and CDs with the mechanism of energy transfer or the mechanism of charge transfer [19], this process can be represented by a simple equation:

$$A^* + Q \rightarrow A + Q \quad \text{or} \quad A^* + Q \rightarrow A + Q \tag{1}$$

where A is CDs, Q is a quencher and * designates an excited state.

The kinetics of this process follows the Stern–Volmer relationship [18–20]:

$$F_0 / F = 1 + k_q \tau_0 [Q] \tag{2}$$

Where F_0 and F are the fluorescence intensities in the absence and presence of quencher, k_q is the quencher rate

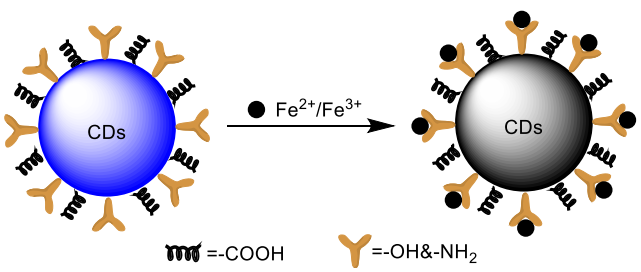

Fig. 2 The CDs are quenched by Fe^{2+} or Fe^{3+} through the static quenching mechanism of CDs

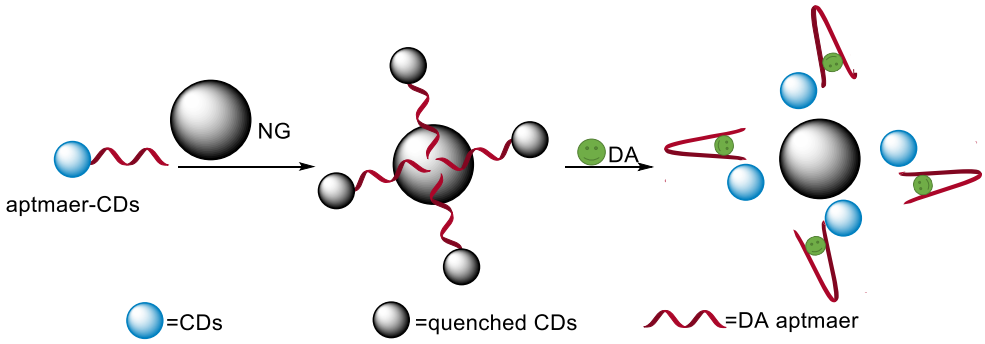

Fig. 3 The aptamer-CDs are quenched by NG through static quenching mechanism of CDs and the fluorescence is recovered after adding the DA

coefficient, τ_0 is the lifetime of the emissive excited state of CDs, without a quencher present, [Q] is the concentration of the quencher.

There are some different characteristics compared to static quenching. (a) The lifetime of CDs would change in the absence and presence of quencher. (b) Dynamic quenching only affected the excited states of the CDs, so no changes in the absorption spectra CDs were observed. (c) A rise of temperature can lead to the increase of the effect of dynamic quenching, as showed in Fig. 1(a).

FRET mechanism of CDs

FRET is an electrodynamic phenomenon that can be explained by using classical physics. FRET occurs between CDs in the excited state and quencher in the ground state when the emission spectrum of CDs overlaps with the absorption spectrum of the quencher. FRET occurs without the appearance of a photon due to long range dipole–dipole interactions between CDs and quencher. The distance between the CDs and quencher was in the range of 10 Å–100 Å [19, 22–24]. The energy transfer efficiency (E) is calculated by following eq. 3. From that the CDs—quencher distance (r) and Förster distance (R_0) between the CDs and the quencher can be estimated by eq. 4–6: [22, 23]

$$E = 1 - \tau_0/\tau \quad (3)$$

$$R_0 = 0.211\left[\kappa^2 n^{-4} \phi\ J(\ )\right]^{1/6} \left(\text{in } \mathring{A} \text{ unit}\right) \quad (4)$$

$$E = 1/\left[1 + (r/R_0)^6\right] \quad \left(\text{in } \mathring{A} \text{ unit}\right) \quad (5)$$

$$\int_0^{\infty} F_D(\ )\varepsilon_A(\ )\ ^4 d \quad (6)$$

τ_0 and τ were the lifetimes in the absence and presence of quencher. κ was the orientation factor of CDs and the quencher transition dipoles and was assumed to be 2/3, Φ was the quantum yield of the CDs, n was the refractive index of the medium, and J(λ) was the integral of overlap values. $F_D(\lambda)$ was the corrected fluorescence intensity of the CDs in the range of λ to λ + Δλ with the total intensity normalized to unity, and $\varepsilon_A(\lambda)$ was the extinction coefficient of the quencher at λ in M^{-1} cm^{-1} .

So, (a) the fluorescence spectral of CDs and the absorbance spectral of the quencher overlapped, (b) the fluorescence lifetime of CDs would decrease and (c) CDs − quencher distance would be in the range of 10 Å–100 Å can demonstrate that the mechanism for CDs-quenching was FRET. There were the CDs can be quenched by 2,4-dinitrophenol(2,4-DNP) [23], this process can demonstrate the theory of FRET mechanism well. The emission spectral of the prepared CDs overlapped with the absorption spectral of 2,4-DNP which can quench the fluorescence of CDs, it met (a). The lifetimes of CDs in the absence and presence of 2,4-DNP were 4.50 ns and 2.46 ns, it met (b). And then the distance between the CDs and 2,4-DNP was calculated to be 26.62 Å by the eq. 3–6, it met (c), this process met the theory of well, so the fluorescence quenching of CDs was attributed to FRET.

Table 2 An overview on CD based assays using static quenching

Types	Particle Size(nm)	Ex/Em(nm)	QY(%)	Analyte	Linear Range	LOD	Ref
N-doped	5.7	360/440	10	Fe^{2+}	0–32 μM	20 nM	[18]
				Fe^{3+}	0–50 μM	35 nM	[18]
N-doped	9.41	360/435	19	Hg^{2+}	0.1–60 μM	18.7 nM	[33]
N, S-doped	2.3	360/437	32	Cu^{2+}	0.2–25 μM	50 nM	[38]
N-doped	1.5–3.0	355/437	-	DA	0.1–5 nM	55 μM	[39]
CDs	1.7–3.9	360/452	-	NA	0.5–10.5 μM	12.6 nM	[41]

Table 3 An overview on CD based assays using dynamic quenching

Types	Particle Size(nm)	Ex/Em(nm)	QY(%)	Analyte	Linear Range	LOD	Ref
B-doped	3.5–4.5	359/437	-	Fe^{3+}	0–16 μM	242 nM	[42]

DET mechanism of CDs

The effect of DET is based on electron transfer, not photon transfer and therefore requires a match between the redox potentials of donor and acceptor.

SET mechanism of CDs

SET is a rather "new" process. It is most often observed with (metal) nanoparticles and involves a metallic surface (such as on gold NPs) and a molecular (organic) dipole. SET was theoretically predicted in 1978 by R. Chance et al. and experimentally proven in the 2000s [25, 26].

PET quenching mechanism of CDs

PET can be explained that between the CDs (electron donor or electron receptor) and the quencher (electron receptor or electron donor) occurred the electron transfer, formed the cation radical and the anion radical respectively. In this process, a complex that can return to the ground state without emission of a photon was formed between the electron donor and the electron receptor. PET contained reductive PET and oxidative PET. Reductive PET was that CDs as an electron receptor got electron from the electron donor. Oxidative PET was contrary to reductive PET. The driving force for reductive electron transfer was the energy gap between the lowest unoccupied molecular orbitals (LUMO) of quencher and the highest occupied molecular orbitals(HOMO) CDs. The driving force for oxidative electron transfer was the energy gap between the LUMO of the CDs and the LUMO of the quencher [19, 27]. So, (a) the lifetimes of CDs decreased, (b) the energy gap of the LUMO and HOMO or the LUMO and LUMO between the CDs and the quencher existed, it would demonstrate that the quenching mechanisms was PET. There were the CDs which can be quenched by picric acid (PA) [27], the process can prove the theory of PET quenching mechanism of CDs well. In order to investigate the quenching mechanism of CDs, the cyclic voltammetry (CV) was used. The E_{red} which was the onset of reduction potential for CDs was measured to be −0.56 V, the E_g which was the energy band gap resulting from the absorption edge in the absorption spectrum of CDs was estimated to be 3.29 eV. The values of the HOMO and LUMO of CDs were calculated to be −7.13 and −3.84 eV according to the empirical formula eq. 7 and eq. 8.

$$E_{HOMO} = -e(E_{ox} + 4.4) \quad (7)$$

$$E_{LUMO} = -e(E_{red} + 4.4) \quad (8)$$

The E_{HOMO} and E_{LUMO} of PA can be calculated to be −8.70 and −5.82 eV, by the B3LYP method in Dmol3 mode. Due to the LUMO of CDs was larger than the LUMO of PA, so the electron can transfer from CDs to PA, it met (b), this process met the oxidative PET.

IFE mechanism of CDs

IFE occurs when the absorption spectrum of quencher in the detection system overlapped with the excitation or emission spectra of CDs. IFE sometimes can be called apparent quenching, it is not a quenching process at all but is rather due to an attenuation of the excitation beam or absorption of emitted radiation by an excess concentration of CDs or by the quencher in solution. [28] This effect also leads to a reduction of intensity (but not decay time), but this effect should not be termed "quenching". Rather, a second absorber is simply filtering off the emission of a particle. This also occurs if distances between emitted and re-absorber exceed 10 nm. Because the process of IFE does not belong to the static or dynamic quenching process, so the absorption peaks of the CDs would not change, it also indicates that there is not new substance to form. So, the fluorescence lifetime of CDs will not be changed. In addition, the Parker equation can further investigate the IFE process [24, 28, 29].

$$\frac{F_{cor}}{F_{obsd}} = \frac{2.3dA_{ex}}{1-10^{-dA_{ex}}} 10^{gA_{em}} \frac{2.3sA_{em}}{1-10^{-sA_{em}}} \quad (9)$$

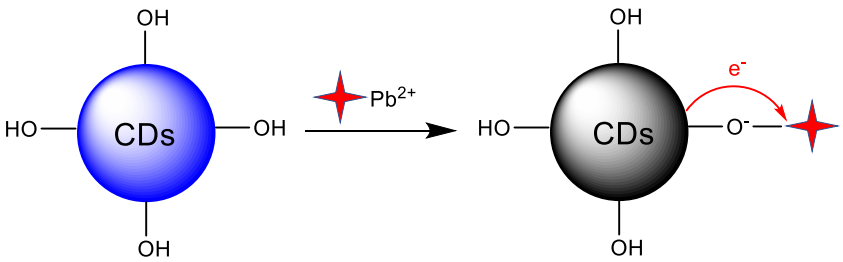

Fig. 4 The CDs are quenched by Pb^{2+} through the PET quenching mechanism of CDs

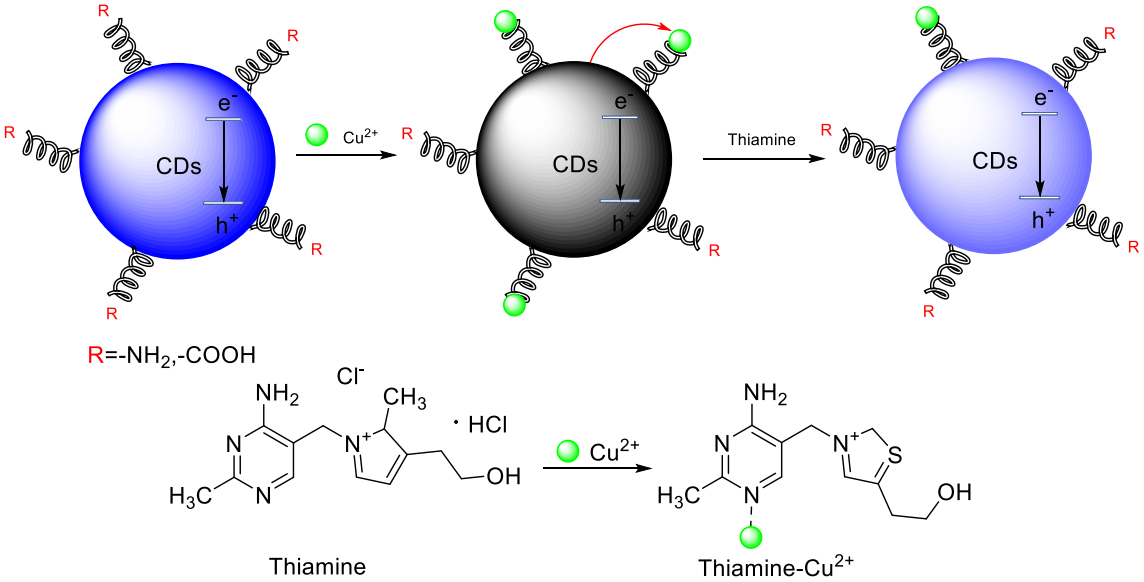

Fig. 5 The CDs are quenched by Cu^{2+} through the PET quenching mechanism of CDs and then the fluorescence is recovered after adding the thiamine

Where F_{obsd} is the observed fluorescence intensity, F_{cor} is the corrected fluorescence intensity after removing IFE from F_{obsd}. A_{em} and A_{ex} are the absorbances at the maximum excitation wavelength (λ_{em}) and maximum emission wavelength (λ_{ex}). "s" is the thickness of the excitation beam. "g" is the distance between the edge of the excitation beam and the edge of cuvette, "d" is the width of the cuvette. So, the effect of IFE increases with the increasing of the value of $F_{cor}/F_{obsd.}$ There are CDs which can be quenched by MnO_2 [29], the demonstration process of IFE is well fit in the theory of IFE. The CDs can be quenched by MnO_2, in order to investigate the quenching mechanism of CDs, the absorption spectra of MnO_2 and fluorescence spectra of CDs was measured then the value of F_{cor}/F_{obsd} was calculated. It can be observed that the absorption spectra of MnO_2 overlapped the excitation and emission of CDs. With the concentrations of MnO_2 increasing from 0 to 40,000 nM, the value of F_{cor}/F_{obsd} increasing from 1.03–1.98, this figure met the Parker equation, so the quenching mechanism of CDs was IFE. The most characteristic differences of these mechanisms are showed in Table 1.

Applications of the quenching mechanisms of CDs in detecting analytes

The fluorescence of CDs can be quenched by analytes which included inorganics and organics. Based on this phenomenon, the CDs can be used as a senor to detect these analytes. In the process of detecting these analytes, the quenching mechanisms of CDs included the static quenching, dynamic quenching, FRET, PET and IFE.

Applications of static quenching mechanism of CDs in detecting analytes

Static quenching mechanism of CDs occurred when a nonfluorescent ground-state complex was formed through the interaction between CDs and quencher [19]. It was facile that the process of verifying the static quenching mechanism of CDs, but it needed the reaction between the CDs and quencher, so the procedures of modifying the CDs were essential, it can lead to the increasing of cost. Due to the easy process of

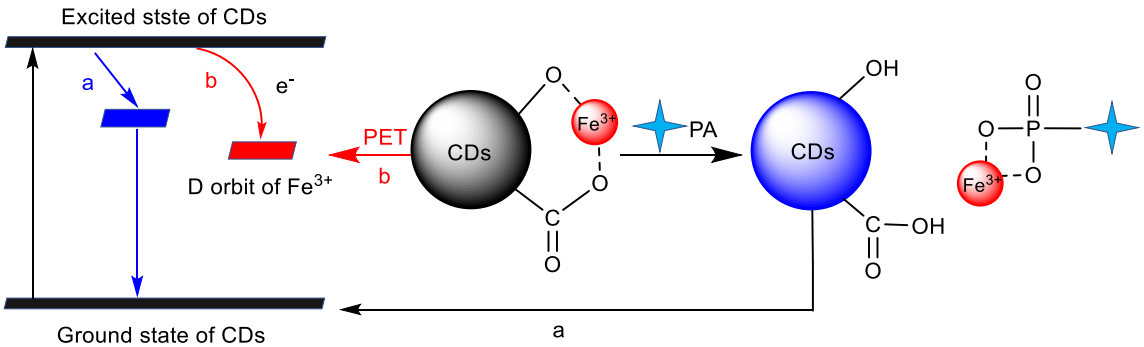

Fig. 6 The CDs are quenched by Fe^{3+} through the PET quenching mechanism of CDs and then the fluorescence is recovered after adding the PA

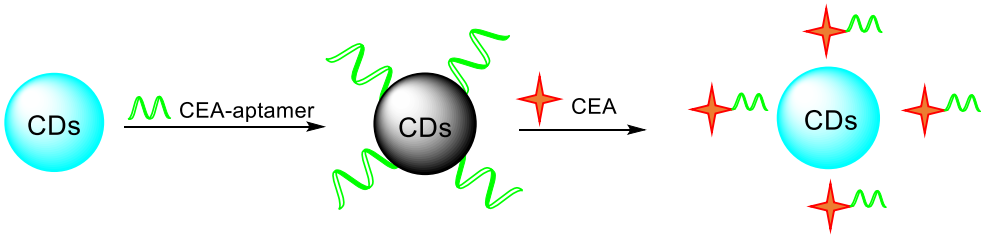

Fig. 7 The CDs are quenched by CEA-aptamer through PET quenching mechanism of CDs and then the fluorescence is recovered after adding the CEA

verifying the static quenching mechanism of CDs, it had been applied for detecting inorganics and organics.

Applications of static quenching mechanism of CDs in detecting inorganics

The inorganics which were detected through static quenching mechanism of CDs included Fe^{2+}, Fe^{3+}, Hg^{2+} and Cu^{2+}. Iron played as a crucial role in human body and iron deficiency was the first one in three global micronutrient deficiencies [30, 31]. Iron can be detected through static quenching mechanism of CDs. Iqbal et al. [18] prepared the CDs with 11,10-phenanthroline (Phen) and anhydrous citric acid (CA) via one step synthetic route. The CDs can be quenched by Fe^{2+} or Fe^{3+} through static quenching mechanism of CDs as showed in Fig. 2. The CDs had been successfully applied for the determination of Fe in real sample of milk.

Mercury (II) ion (Hg^{2+}) was one of the most ubiquitous and dangerous pollutants which can lead environmental and health concerns [32–35]. Hg^{2+} can be detected through static quenching mechanism of CDs. Gu et al. [33] prepared the fluorescent nitrogen-doped carbon dots (CDs) with lotus root (LR) through one-pot microwave method and then formed the LR-CDs. The fluorescent of the LR-CDs can be quenched by Hg^{2+} through static quenching mechanism of CDs. The LR-CDs can be applied for multicolor A549 cell imaging.

Copper (Cu^{2+}) was essential in our life, but excessive Cu^{2+} can cause potential risk to animals and plants [36, 37]. Through the static quenching mechanism of CDs, Cu^{2+} can be detected. Wang et al. [38] prepared the CDs with thiourea and diethylene glycol via microwave irradiation. The fluorescence of the CDs can be quenched by Cu^{2+} through the static quenching mechanism.

Applications of static quenching mechanism of CDs in detecting organics

The organics which were detected through the static quenching mechanism of CDs included dopamine(DA) and nicotinic acid.

Dopamine (DA) as the most important neurotransmitter in the central nervous system was a precursor of norepinephrine in the biological pathway and played an important role in cardiovascular, central nervous system and endocrine system [39, 40], it can be detected through the static quenching mechanism of CDs. Zhu et al. [39] structured a strategy based on dopamine(DA) aptamer labeled CDs, aptamer-CDs. The CDs were prepared with citric acid monohydrate and diethylene triamine via hydrothermal method. The aptamer-CDs can be quenched by nano-graphite (NG) through static quenching mechanism of CDs. When DA was added into this system, due to the higher affinity of DA for its aptamer, DA aptamer can be removed from the CDs and then the fluorescence was recovered as showed in Fig. 3. This method can be applied to detect the determination of DA in human urine samples.

Zuo et al. [41] fabricated the CDs with citric acid via hydrothermal method, then the CDs were functionalized by 3-aminopropyl triethoxysilane (APTES), the functionalized CDs were coated with a shell of molecularly imprinted sol-gel, nicotinic acid (NA) was then removed by extraction and spherical silica nanoparticles (SiNPs). The SiNPs can be quenched by NA through static quenching mechanism. The composite was successfully utilized as a fluorescent probe for the determination of NA in spiked human urine samples.

The static quenching mechanism of CDs occurs when a nonfluorescent ground-state complex is formed through the interaction between CDs and quencher. It needs the reaction between the CDs and the quencher. So it is convenient to

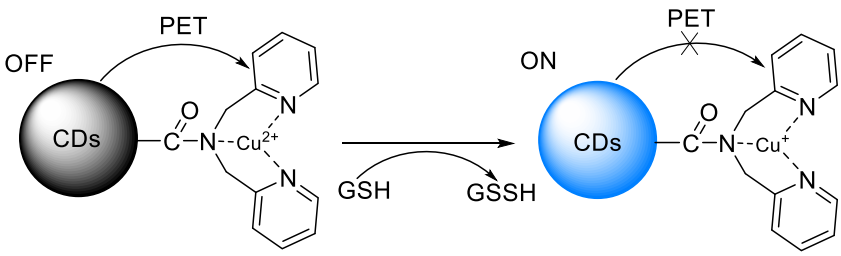

Fig. 8 The BPMA-CDs are quenched by Cu^{2+} through PET quenching mechanism of CDs and then the fluorescence is recovered after adding the GSH

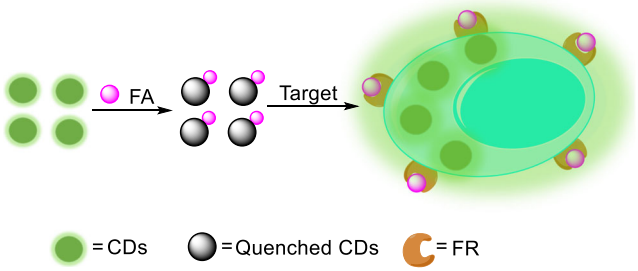

Fig. 9 The CDs are quenched by FA through PET quenching mechanism of CDs and then the fluorescence is recovered after FA reacting with FR

design the on-off type probe, the substance with a stronger affinity can recovery the fluorescent of CDs (Table 2).

Applications of dynamic quenching mechanisms of CDs in detecting analytes

Different from the static quenching mechanism of CDs, the quencher in dynamic quenching mechanisms of CDs cannot react with CDs. The dynamic quenching mechanism of CDs can be used for detecting inorganics. Wang et al. [42] prepared the B-CDs with glucose and boric acid via hydrothermal method. The B-CDs can be quenched by Fe^{3+} in water through dynamic quenching mechanism.

In the design of the dynamic quenching mechanism, the absorption spectrum of the quencher and the excitation and emission spectra of CD are not necessarily required. This mechanism is susceptible to temperature influences. At present, it is simple to judge the occurrence of dynamic quenching by changing the fluorescence lifetime before and after the action of the quencher (Table 3).

Applications of PET quenching mechanisms of CDs in detecting analytes

The analytes which were detected through PET quenching mechanisms of CDs included inorganics and organics. Inorganics included Pb^{2+}. Organics included thiamine, phytic acid (PA), carcinoembryonic antigen (CEA) and glutathione (GSH).

Applications of PET quenching mechanisms of CDs in detecting inorganics

Lead as one of the most common toxic heavy metals can be accumulated in human nervous and cardiovascular systems when exposed to contaminated air and water sources owing to its non-biodegradability [43–46], detecting for it can be realized through the PET quenching mechanism of CDs. Liu et al. [46] prepared a kind of CDs with chocolate through a one-step hydrothermal method. The CDs can be quenched by Pb^{2+} through PET quenching mechanism of CDs as showed in Fig. 4. This method can be used to detect Pb^{2+} in real water samples.

Applications of PET quenching mechanisms of CDs in detecting organics

Thiamine was important to prevent the diseases such as beriberi, neurological disorders [47, 48], detecting for it can be realized through the PET quenching mechanism of CDs. Purbia et al. [47]. prepared luminescent CDs with tender coconut water via microwave-assisted hydrothermal method. The CDs can be quenched by Cu^{2+} through PET quenching mechanism of CDs and then recovered after adding the thiamine as show in Fig. 5. The method can be applied to the detecting thiamine in blood serum and urine.

Phytic acid (PA) was the principal storage form of phosphorus in plant tissues and played a positive role in normal physiological processes [49–51], detecting for it can utilize the PET quenching mechanism of CDs. Gao et al. [49] prepared the CDs using citric acid and lysine via one-step pyrolysis. The prepared CDs was found that it can be effectively quenched by Fe^{3+} through PET quenching mechanism of CDs, when phytic acid (PA) was added to the CDs/Fe^{3+} system, due to PA had a stronger affinity for Fe^{3+} ions compared to CDs, so Fe^{3+} were released from the CDs/Fe^{3+} system and then the fluorescence of the CDs was significantly recovered as showed in Fig. 6. This method can be used the standard and real PA samples.

Carcinoembryonic antigen (CEA) as a tumor-associated antigen, was expressed in lung cancer, ovarian carcinoma,

Table 4 An overview on CD based assays using PET

Types	Particle Size(nm)	Ex/Em(nm)	QY(%)	Analyte	Linear Range	LOD	Ref
CDs	6.41	280/354	-	Pb^{2+}	33–1670 nM	12.7 nM	[46]
N-doped	2–6	390/450	2.8	Thiamine	1–50 μM	280 nM	[47]
N-doped	3.2	350/450	-	PA	0.68–18.69 μM	360 nM	[49]
CDs	3	367/440	13.9	CEA	0.1–5 ng•mL^{-1}	0.3 ng•mL^{-1}	[52]
BPMA functionalized	2–5	332/414	-	GSH	0–13.3 nM	42 nM	[55]
CDs	3.5	410/520	5.4	FR	0.2 to 1.3 mg•mL^{-1}	-	[59]

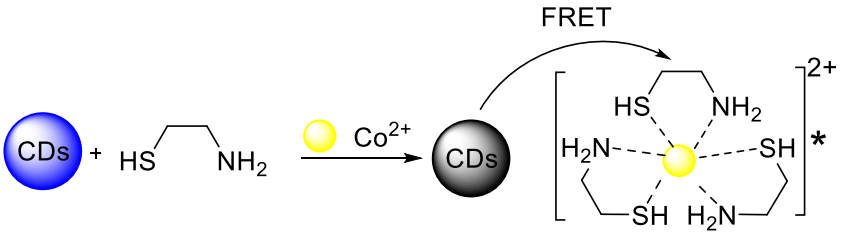

Fig. 10 The N, S-CDs are quenched by Co^{2+} in the present of cysteamine through the FRET mechanism of CDs

breast cancer, and cystadenocarcinoma and was critical for clinical purposes [52, 53], CEA can be detected through the PET quenching mechanism of CDs. Miao et al. [52] prepared the carbon dots (CDs) with tomato juice via hydrothermal method. The prepared CDs can be quenched by CEA-aptamer (carcinoembryonic antigen-aptamer) through PET quenching mechanism of CDs. When CEA was added into this system, the stronger binding affinity between CEA and CEA-aptamer would remove the CEA-aptamer from CDs and then the fluorescent of CDs was recovered as showed in Fig. 7. This method can be used for detecting the CEA in real blood samples and human lung cancer cell imaging.

Glutathione (GSH) as a thiolcontaining tripeptide played a vital role in defending cellular components against reactive oxygen species (ROS) and toxins [54–58], the CDs which was used to detect GSH can be designed via the PET quenching mechanism of CDs. Huang et al. [55] prepared the CDs with oxidized activated carbon, then the CDs were functionalized by bis(3-pyridylmethyl) amine and then BPMA-CDs which can be quenched by Cu^{2+} through PET quenching mechanism of CDs. When GSH was added into the system, GSH can reduce Cu^{2+} to Cu^{+}, made the process of PET was prohibited. So, the fluorescent of the BPMA-CDs was recovered as showed in Fig. 8. This method can be utilized to monitor GSH level in live cells.

Folate receptor (FR) as a tumor marker, it played an important role in cancer diagnosis and therapy [59, 60], the method can be designed through the PET quenching mechanism of CDs. Liu et al. [59] prepared the CDs with Glu and a passivating agent – poly (acrylate sodium) (PAAS) via microwave assisted hydrothermal method. Using the prepared CDs to react with folic acid(FA) via hydrogen-bond form the FA-CDs, it leaded the quenching of CDs through PET quenching mechanism of CDs. When the FA-CDs met the folate receptor (FR), the FA can combine with FR, it made the fluorescence of CDs recover as showed in Fig. 9. On this basis, the FA-CDs can accurately distinguish the FR on the surface of cancer cells and then the CDs permeated into the tumor cells. On this basis, the FA-CDs can distinguish the tumor cells. The FA-CDs can be used for imaging of HeLa and HepG2 cells.

In the design of the photoinduced electron transfer mechanism, the CD surface is usually rich in electron donor groups, and the quencher is an organic small molecule with an electron withdrawing group on its surface. This mechanism may be extensively developed for organic small molecule detection (Table 4).

Applications of FRET quenching mechanisms of CDs in detecting analytes

The analytes which were detected through FRET mechanisms of CDs included inorganics and organics. Inorganics included Co^{2+}, Sulfide ions, Cu^{2+} and ammonia. Organics included

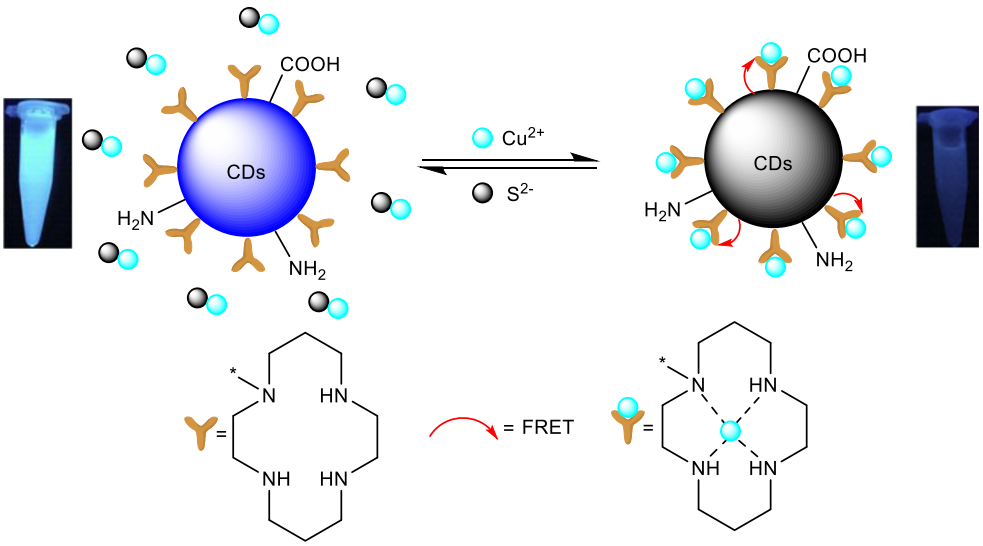

Fig. 11 The CCDs are quenched by Cu^{2+} through FRET mechanism of CDs and then the fluorescence of CCDs is recovered after adding sulfide

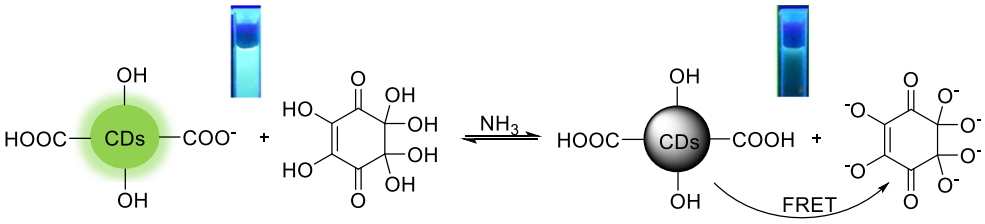

Fig. 12 The CDs are quenched by ammonia through FRET quenching mechanism of CDs

GSH, tetracyclines, 2,4,6-Trinitrophenol (TNP), glyphosate (Gly), kanamycin and adenosine 5′-triphosphate (ATP).

Applications of FRET mechanisms of CDs in detecting inorganics

The uptake of Cobalt (Co) was an essential element, but excessive uptake of Co can cause various diseases, such as asthma, decreased pulmonary function and thyroid damage [61–63], the FRET mechanisms of CDs can be applied for detecting Co^{2+}. Chen et al. [61] prepared a highly luminescent nitrogen and sulfur co-doped carbon dots (N, S-CDs). The CDs were prepared with citric acid and l-cysteine via hydrothermal method. Co^{2+} can react with cysteamine to form a complex ($Co(cys)_3^{2+}$). The absorption spectrum of the complex($Co(cys)_3^{2+}$) covered completely the emission spectrum of N, S-CDs. The N, S-CDs can be quenched by Co^{2+} in the presence of cysteamine through FRET mechanism of CDs as showed in Fig. 10. On this basis, the N, S-CDs acted as the energy donor and $Co(cys)_3^{2+}$ acted as the energy acceptor.

Sulfide existed in the environment through wide ways, such as it can be from biological metabolism and industrial processes [64]. Copper ion (Cu^{2+}) as the abundant transition metal ion in the human body, is essential in biological reactions, however, abnormal concentration of Cu^{2+} can cause adverse effects to biological system. They can be detected via the FRET mechanism of CDs. Chen et al. [65] synthesized the CDs with citric acid monohydrate and ethylenediamine via a modified microwave-assisted method. Then using 1,4,8,11-tetraazacyclotetradecane (cyclam) to functionalize the CDs formed the CCDs. Cu^{2+} can reacted with cyclam and formed Cu^{2+}-cyclam complex, FRET process can be effectively taken place between the CDs and the surface Cu^{2+}-cyclam complex, so the CDs can be quenched by Cu^{2+} through FRET mechanism of CDs. Sulfide ions can remove Cu^{2+} from the CCDs-Cu^{2+} complex and recover the fluorescence of CDs as showed in Fig. 11. This method can be used for HeLa cell imaging.

It was crucial for environment, industrial and biomedical purposes to detect ammonia [66, 67], it can be detected through the FRET mechanism of CDs. Ganiga et al. [66] designed a detecting platform with CDs and sodium rhodizonate. When ammonia was present in this system, FRET between CDs and sodium rhodizonate would occur and led the fluorescence quenching of CDs as showed in Fig. 12. So, this method can be used for detecting ammonia through FRET mechanism of CDs.

Applications of FRET mechanisms of CDs in detecting organics

GSH can also be detected through the FRET quenching mechanism of CDs. Yang et al. [68] designed the strategy based on CDs–MnO_2 nanocomposites which were obtained by the reaction between the CDs and MnO_2 nanocomposites. The fluorescence of CDs can be quenched by MnO_2 through FRET quenching mechanism of CDs. When GSH was added into this system, MnO_2 can be reduced to Mn^{2+} by GSH and then FRET was prohibited. So, the fluorescence of CDs was recovered. This method had been used to monitor intracellular GSH level in living cells. Qu.et al. [69] prepared the CDs with ascorbic acid and ethylene glycol through one-pot hydrothermal method. The CDs have blue fluorescent with the

Table 5 An overview on CD based assays using FRET

Types	Particle Size(nm)	Exc /Em(nm)	QY (%)	Analyte	Linear Range	LOD	Ref
N, S-doped	4–8	345/420	-	Co^{2+}	0.08–100 μM	80 nM	[61]
N-doped	-	370/460	-	Cu^{2+}/sulfide	0.7–4 μM/0–15 μM	100 nM/130 nM	[65]
CDs	3–4	400/490	5.28	ammonia	0–150 ppm	3 ppm	[66]
CDs	-	325/458	-	GSH	0.03–974.1 μM	15 nM	[68]
CDs	1.81	315/385	-	tetracyclines	-	-	[69]
N-doped	-	380/440	-	kanamycin	4–25 μM	1.1 μM	[73]
N-doped	6	340/410	52	glyphosate	0.02–2 μM	0.6 μM	[72]
CDs	3.2	310/358	21.8	TNP	0.2–17 μM	16.9 nM	[70]
CDs	2	295–547	-	ATP	0.04–4 μM	8.5 nM	[74]

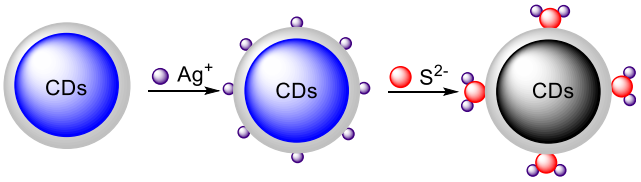

Fig. 13 The CDs are quenched by sulfide in the present of Ag^+ through IFE quenching mechanism of CDs

excitation wavelength at 315 nm. The CDs can be quenched by tetracyclines through FRET mechanism of CDs.

2,4,6-Trinitrophenol (TNP) causes adverse effects on the environment and on health [70, 71]. It can be detected through FRET quenching mechanism of CDs. Shi et al. [70] prepared the CDs with sucrose phosphate solution via hydrothermal treatment method. The fluorescence of CDs can be significantly quenched by 2,4,6-trinitrophenol (TNP) through FRET quenching mechanism of CDs. The prepared CDs solution can replace traditional colorings and had been successfully applied for *Escherichia coli* labeling and intracellular imaging.

Expect the static quenching mechanism of CDs, glyphosate (Gly) can also be detected through FRET quenching mechanism of CDs. Yuan et al. [72] synthesized CDs using citric acid and Tris via one-step hydrothermal method. The fluorescence intensity of the CDs can be effectively quenched by Gly through FRET quenching mechanism of CDs. This system can also enable the design of an "AND" logic gate and be used for rapid screening of glyphosate in real water samples.

Wang et al. [73] synthesized the CDs with sodium citrate and NH_4HCO_3 through one-step hydrothermal method. Amino-modified aptamer was labeled on carbon dots by amidation reaction between the carboxyl group of carbon dots and side amino group of DNA probes. The aptamer-CDs can be quenched by MoS_2 nanosheets through FRET mechanism, when kanamycin was added into this system, kanamycin can combine with the aptamer, it leads to the recovery of the fluorescent of CDs, through this phenomenon, this method displays good specificity and can be applied to the determination of kanamycin in spiked milk.

Adenosine 5′-triphosphate (ATP) which was the mediator of energy exchanges in metabolic processes acted as an important character for biological determination to disease diagnosis [74–76], it can be detected through the FRET quenching mechanism of CDs. Xu et al. [74] prepared the terbium ion-coordinated CDs (Tb-CDs) with Tb^{3+} via the microwave method. The strategy consisted of ATP aptamer, gold nanoparticles (AuNP) and Tb-CD. In absence of ATP, AuNP tended to aggregate and then the FRET between Tb-CDs and AuNP were prohibited, so the Tb-CDs had fluorescent. When ATP was added, the FRET between Tb-CDs and AuNP occurred, so the Tb-CDs were quenched by FRET quenching mechanism of CDs. This method had been applied for detecting ATP in human serum.

CDs-based FRET probe can realize big changes in Stokes. This mechanism can provide a simple and effective method for the visual detection (Table 5).

Applications of IFE mechanism of CDs in detecting analytes

IFE occurs when the absorption spectrum of quencher in the detection system overlapped with the excitation or emission spectra of CDs. IFE mechanism of CDs occurred when the absorption spectrum of quencher in the detection system overlapped with the excitation or emission spectra of CDs. IFE mechanism of CDs was different from static and dynamic quenching mechanism of CDs, it did not require the modifications of CDs, the complicated instruments or vast calculations, so it was less costly and complicated. Inorganics and organics also can be detected through IFE quenching mechanism of CDs. Inorganics included Cr(VI) and sulfide. Organics included ascorbic acid (AA), fluazinam, picric acid(PA), hemoglobin(HGB), β-glucuronidase (GLU) and alkaline phosphatase(ALP).

Applications of IFE mechanism of CDs in detecting inorganics

Chromium as the major water pollutants because of its widespread use in modern industries [77, 78], it can be detected through IFE mechanism of CDs. Zhang et al. [77] fabricated the cobalt(II)-doped carbon dots (CCDs) with PAN and cobalt chloride via hydrothermal method. The CCDs can be quenched by Cr(VI) through IFE quenching mechanism of CDs. This CCDs can be used to rapidly detecting Cr(VI) ions in tap water and fish samples. In order to get lower limit of detecting, Chen et al. [79] prepared nitrogen and sulfur co-doped carbon dots (N, S-CDs) with citric acid and cystamine dihydrochloride through one-pot hydrothermal method. The emission spectrum of N, S-CDs overlapped with the

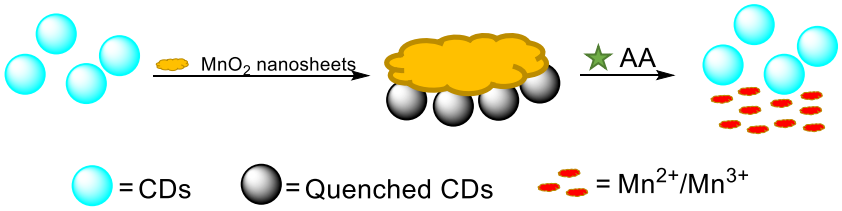

Fig. 14 The CDs are quenched by MnO_2 nanosheets through IFE quenching mechanism of CDs and then the fluorescence is recovered after adding the AA

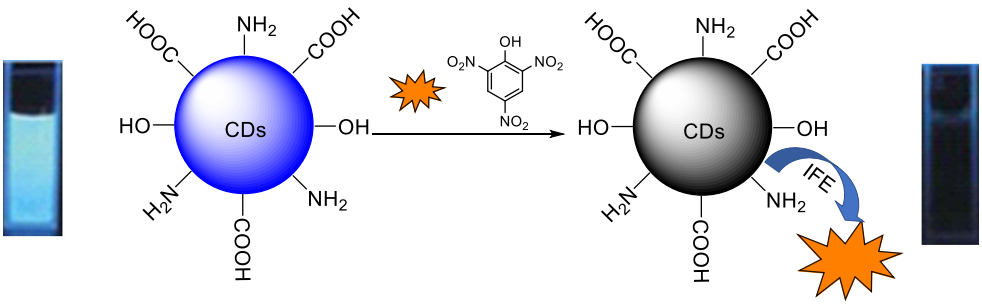

Fig. 15 The CDs are quenched by PA through IFE quenching mechanism of CDs

absorption spectrum of Cr(VI). The fluorescence of N, S/C-dots can be quenched by Cr(VI) based on IFE mechanism of CDs. The N, S-CDs can be applied to the cell imaging.

Expect the FRET quenching mechanism of CDs, sulfide can also be detected through IFE quenching mechanism of CDs. Barati et al. [64] synthesized the CDs with lime juice through a one-pot hydrothermal method. The fluorescence of the CDs had little change in the present of Ag^+, when sulfide was added into this system, sulfide can react with A^+ form Ag_2S particles which absorbed both the excitation wavelength and emission spectrum of CDs, so Ag_2S particles can quench the CDs through IFE quenching mechanism of CDs as showed in Fig. 13. This method had been applied for determination of sulfide ion concentration in tap and mineral waters.

Applications of IFE mechanism of CDs in detecting organics

Ascorbic acid (AA) which was vitamin C was a strong antioxidant that can reduce oxidative stress in body and the deficiency of AA would lead to the scurvy [80–82], it can be detected through IFE quenching mechanism of CDs. Liu et al. [29] prepared the CDs with sodium citrate and NH_4HCO_3 through a one-step hydrothermal method. The prepared CDs can be first quenched by addition of MnO_2 nanosheets through IFE quenching mechanism of CDs and then formed a CQDs-MnO_2 probe. When ascorbic acid(AA) was added into the quenched CQDs solution, the MnO_2 was destroyed due to the redox reaction between AA and MnO_2 nanosheets, and the fluorescence of the CDs was recovered as showed in Fig. 14. The method had benn successfully applied to the analysis of AA in fresh fruits, vegetables, and commercial fruit juices samples.

Fluazinam can target liver, lung, brain uterus and cause dermatitis asthma in human [83, 84], it can be detected through IFE quenching mechanism of CDs. Zou et al. [83] prepared the carbon dots doped with nitrogen and sulfur(NSCDs) with L-cysteine via a hydrothermal method. The fluorescence of the NSCDs can be quenched by fluazinam through strong IFE quenching mechanism of CDs. On this basis, the NSCDs can be used to detect fluazinam. The NSCDs can be used to detect the fungicide in soil and apple samples, it can also be used for fabricating visual paper-based testing stripes under a portable UV lamp.

Expect the FRET quenching mechanism, picric acid(PA) can be also detected through IFE mechanism of CDs. Fan et al. [27] synthesized the CDs using malonic acid and urea via one-pot hydrothermal method. The fluorescence of CDs can be selectively quenched by PA through IFE mechanism of CDs with 10s as showed in Fig. 15. This method had been successfully applied for detecting of PA in real water samples.

Expect the static quenching mechanism, hemoglobin(HGB) can also be detected through the IFE mechanism of CDs. Barati et al. [85] utilized the CDs which were synthesized with citric acid and ethylenediamine via a one-step hydrothermal method

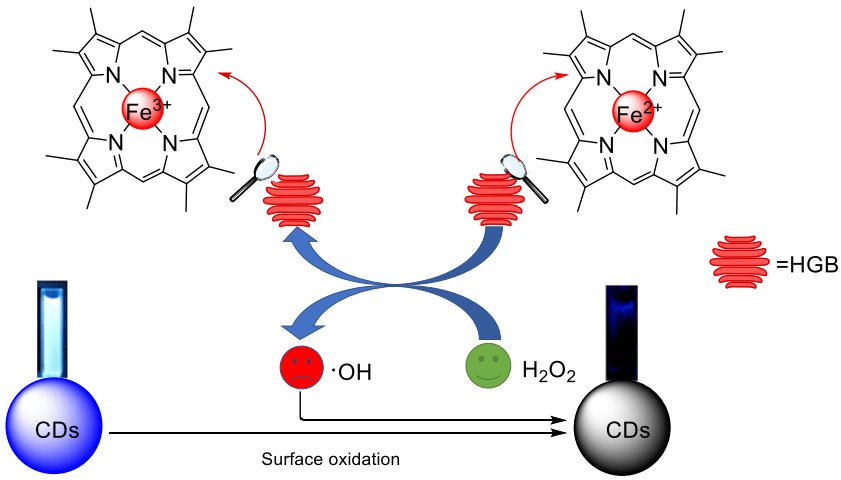

Fig. 16 The CDs are quenched by HGB through IFE quenching mechanism of CDs and the CDs can be strongly quenched by HGB in the present of H_2O_2

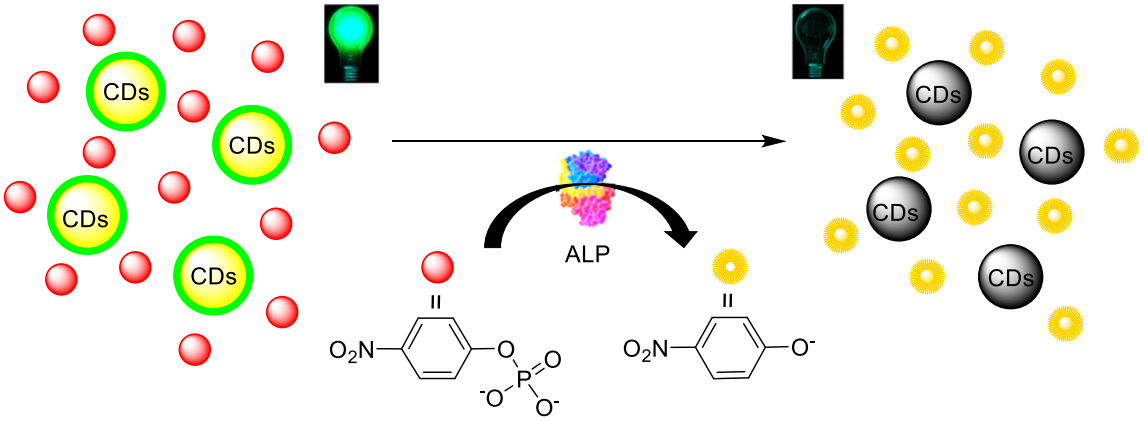

Fig. 17 The N-CDs are quenched by ALP in present of PNPP through IFE quenching mechanism of CDs.

according to a previous method. Although the fluorescence of CDs can be quenched by HGB through IFE mechanism of CDs, the presence of H_2O_2 resulted in high fluorescence quenching of CDs due to the reaction of HGB with H_2O_2 that generated reactive oxygen species including hydroxyl (•OH) and superoxide ($O•_2^-$) radicals under heme degradation and/or iron release from HGB and the subsequent reaction of hydroxyl radicals as showed in Fig. 16. The method had been applied for the detection of HGB in human blood samples.

Alkaline phosphatase (ALP) was an important biomarker for diagnostics, the level of ALP in serum was related to breast, prostatic cancer and bone disease [86–88], Li et al. [86] prepared the N-doped CDs(N-CDs) with ethanediamine and catechol via hydrothermal method. The system of N-CDs and p-Nitrophenylphosphate (PNPP) was structed. PNPP cannot quench the fluorescence of CDs, when alkaline phosphatase (ALP) was added in this system, ALP can catalyze PNPP to product p-nitrophenol (PNP). It was found that PNP can quench the fluorescence of CDs through the IFE quenching mechanism of CDs as showed in Fig. 17. The method had been successfully applied to ALP sensing in serum samples.

The process of the IFE quenching of CDs did not require the modifications of CDs and the process of verifying the IFE quenching of CDs didn't need vast calculations, so it was less costly and complicated that utilizing the IFE quenching of CDs to design strategy (Table 6).

Conclusion

The fluorescence of CDs can be quenched by quenchers through static quenching, dynamic quenching, Förster resonance energy transfer(FRET), photoinduced electron transfer(PET), surface energy transfer (SET), dexter energy transfer (DET) and inner filter effect(IFE). The static quenching mechanism of CDs was facile to verify, but the process of the static quenching of CDs needed the reaction between the CDs and quencher, so the procedures of modifying the CDs were essential, it can lead to increasing the complexity of the operation, through the static quenching mechanism of CDs, Hg^{2+}, Fe^{2+}, Fe^{3+}, Cu^{2+}, glyphosate, dopamine, tartrazine and hemoglobin can be detected. Different from the static quenching mechanism of CDs, the quenchers which were used in the process of dynamic quenching of CDs didn't need to react with CDs, but the process of verifying FRET and PET mechanism of CDs is complicated, which needed to calculate the values of HOMO, LUMO, energy transfer efficiency and Förster distance etc. Through the FRET and PET

Table 6 An overview on CD based assays using IFE

Types	Particle Size(nm)	Ex/Em(nm)	QY(%)	Analyte	Linear Range	LOD	Ref
N, S-doped	1.7	350/443	2.6	Cr(VI)	1–80 μM	860 nM	[79]
Co (II) -doped	2.93	485/564	6.2	Cr(VI)	5–125 μM	1.17 μM	[77]
N-doped	7.6	345/443	-	sulfide	1–10 μM	430 nM	[64]
N-doped	1.4	360/441	-	AA	0.18–90 μM	42 nM	[29]
N, S-doped	4.7	350/440	15.2	fluazinam	0.05–4 μM	10 nM	[83]
N-doped	2.5	320/395	12.6	PA	0.1–26.5 μM	51 nM	[27]
N-doped	5	345/442	-	HGB	1–100 nM	0.4 nM	[85]
N-doped	5–7	405/510	49	ALP	0.01 to 25 $U•L^{-1}$	0.001 $U•L^{-1}$	[86]

mechanism of CDs, Hg^{2+}, Co^{2+}, Cu^{2+}, Sulfide ions, Pb^{2+}, thiamine, phytic acid, adenosine 5′-triphosphate, glyphosate, carcinoembryonic antigen, glutathione and folate receptor (FR) can be detected. In contrary to the other mechanisms, the process of the IFE quenching of CDs did not require the modifications of CDs and the process of verifying the IFE quenching of CDs didn't need vast calculations, so it was less costly and complicated that utilizing the IFE quenching of CDs to design strategy. Cr^{6+}, Sulfide ions, ascorbic acid, fluazinam, picric acid, hemoglobin, β-glucuronidase and alkaline phosphatase can be detected through the IFE quenching mechanism of CDs. Although all of these quenching mechanisms can be used for detecting ions, small molecules and biomacromolecules, but the process of utilizing the IFE quenching of CDs to design method was facile, it would be expected to apply to the further fields in the future.

Acknowledgements The work described in this manuscript was supported by the National Natural Science Foundation of China (21374078), The Science and Technology Plans of Tianjin (No. 15JCYBJC18100).

Compliance with ethical standards The authors confirm that this article content has no conflict of interest.

References

1. Zhou J, Zhou H, Tang J, Deng S, Yan F, Li W, Qu M (2017) Carbon dots doped with heteroatoms for fluorescent bioimaging: a review. Microchim Acta 184:343–368
2. Zuo P, Lu X, Sun Z, Guo Y, He H (2016) A review on syntheses, properties, characterization and bioanalytical applications of fluorescent carbon dots. Microchim Acta 183:519–542
3. Wang Z, Xu C, Lu Y, Chen X, Yuan H, Wei GU, Ye G, Chen J (2017) Fluorescence sensor array based on amino acid derived carbon dots for pattern-based detection of toxic metal ions. Sensors Actuators B 241:1324–1330
4. Li S, Luo J, Yin G, Xu Z, Le Y, Wu X, Wu NC, Zhang Q (2015) Selective determination of dimethoate via fluorescence resonance energy transfer between carbon dots and a dye-doped molecularly imprinted polymer. Sensors Actuators B 206:14–21
5. Simões EF, Leitão JM, da Silva JCE (2016) Carbon dots prepared from citric acid and urea as fluorescent probes for hypochlorite and peroxynitrite. Microchim Acta 183(5):1769–1777
6. Hao T, Wei X, Nie Y, Xu Y, Yan Y, Zhou Z (2016) An eco-friendly molecularly imprinted fluorescence composite material based on carbon dots for fluorescent detection of 4-nitrophenol. Microchim Acta 183(7):2197–2203
7. Yao W, Wu N, Lin Z, Chen J, Li S, Weng S, Lin X (2017) Fluorescent turn-off competitive immunoassay for biotin based on hydrothermally synthesized carbon dots. Microchim Acta 184(3): 907–914
8. Larki A (2017) A novel application of carbon dots for colorimetric determination of fenitrothion insecticide based on the microextraction method. Spectrochim Acta A 173:1–5
9. Hou J, Dong J, Zhu H, Teng X, Ai S, Mang (2015) A simple and sensitive fluorescent sensor for methyl parathion based on L-tyrosine methyl ester functionalized carbon dots. Biosens Bioelectron 68: 20–26
10. Chang MMF, Ginjom IR, Ng SM (2017) Single-shot 'turn-off' optical probe for rapid detection of paraoxon-ethyl pesticide on vegetable utilising fluorescence carbon dots. Sensors Actuators B 242:1050–1056
11. Baker SN, Baker GA (2010) Luminescent carbon nanodots: emergent nanolights. Angew Chem 49(38):6726–6744
12. Cao B, Yuan C, Liu B, Jiang C, Guan G, Han MY (2013) Ratiometric fluorescence detection of mercuric ion based on the nanohybrid of fluorescence carbon dots and quantum dots. Anal Chim Acta 786:146–152
13. Ahmed GHG, Laíño RB, Calzón JAG, García MED (2015) Highly fluorescent carbon dots as nanoprobes for sensitive and selective determination of 4-nitrophenol in surface waters. Microchim Acta 182(1–2):51–59
14. Speranskaya ES, Beloglazova NV, Lenain P, De SS, Wang Z, Zhang S, Hens Z, Knopp D, Niessner R, Potapkin DV, Goryacheva IY (2014) Polymer-coated fluorescent CdSe-based quantum dots for application in immunoassay. Biosens Bioelectron 53:225–231
15. Wang R, Wang X, Sun Y (2017) Aminophenol-based carbon dots with dual wavelength fluorescence emission for determination of heparin. Microchim Acta 184(1):187–193
16. Parvin N, Mandal TK (2017) Dually emissive P, N-co-doped carbon dots for fluorescent and photoacoustic tissue imaging in living mice. Microchim Acta 184(4):1117–1125
17. Lin Y, Yao B, Huang T, Zhang S, Cao X, Weng W (2016) Selective determination of free dissolved chlorine using nitrogen-doped carbon dots as a fluorescent probe. Microchim Acta 183(7):2221–2227
18. Iqbal A, Tian Y, Wang X, Gong D, Guo Y, Iqbal K, Wang Z, Liu W, Qin W (2016) Carbon dots prepared by solid state method via citric acid and 1,10-phenanthroline for selective and sensing detection of Fe^{2+} and Fe^{3+}. Sensors Actuators B 237:408–415
19. Lakowicz JR (2006) Principles of fluorescence spectroscopy. Maryland, USA
20. Liu W, Diao H, Chang H, Wang H, Li T, Wei W (2017) Green synthesis of carbon dots from rose-heart radish and application for Fe^{3+} detection and cell imaging. Sensors Actuators B 241:190–198
21. Huang S, Wang L, Huang C, Xie J, Su W, Sheng J, Xiao Q (2015) A carbon dots based fluorescent probe for selective and sensitive detection of hemoglobin. Sensors Actuators B 221:1215–1222
22. Diac A, Focsan M, Socaci C, Gabudean AM, Farcau C, Maniu D, Vasile E, Terec A, Veca LM, Astilean S (2015) Covalent conjugation of carbon dots with rhodamine B and assessment of their photophysical properties. RSC Adv 5(95):77662–77669
23. Liang Z, Kang M, Payne GF, Wang X, Sun R (2016) Probing energy and electron transfer mechanisms in fluorescence quenching of biomass carbon quantum dots. ACS Appl Mater Inter 8(27): 17478–17488
24. Liu H, Xu C, Bai Y, Liu L, Liao D, Liang J, Liu L, Han H (2017) Interaction between fluorescein isothiocyanate and carbon dots: inner filter effect and fluorescence resonance energy transfer. Spectrochim Acta A 171:311–316
25. Chance R, Prock A, Silbey R (1978) Molecular fluorescence and energy transfer near interfaces. Adv Chem Phys 60:1
26. Chen Y, O'Donoghue MB, Huang YF, Kang H, Phillips JA, Chen X (2010) A surface energy transfer nanoruler for measuring binding site distances on live cell surfaces. J Am Chem Soc 132(46):16559–16570
27. Fan YZ, Zhang Y, Li N, Liu SG, Liu T, Li NB, Luo HQ (2017) A facile synthesis of water-soluble carbon dots as a label-free fluorescent probe for rapid, selective and sensitive detection of picric acid. Sensors Actuators B 240:949–955
28. Gauthler TD, Shane EC, Guerln WF, Seltz WR, Grant CL (1986) Fluorescence quenching method for determining equilibrium

constants for polycyclic aromatic hydrocarbons binding to dissolved humic materials. Environ Sci Tec 20(11):1162–1166
29. Liu J, Chen Y, Wang W, Feng J, Liang M, Ma S, Chen X (2016) "switch-on" fluorescent sensing of ascorbic acid in Food samples based on carbon quantum dots-MnO2 probe. J Agr Food Chem 64(1):371–380
30. Li L, Wang C, Liu K, Zhu R, Qiang H, Lin Y (2015) Synthesis of nitrogen-doped and amino acid-functionalized graphene quantum dots from glycine, and their application to the fluorometric determination of ferric ion. Microchim Acta 182(3–4):763–770
31. Xia J, Zhuang YT, Yu YL, Wang JH (2017) Highly fluorescent carbon polymer dots prepared at room temperature, and their application as a fluorescent probe for determination and intracellular imaging of ferric ion. Microchim Acta 184(4):1109–1116
32. Yan F, Kong D, Luo Y, Ye Q, He J, Guo X, Chen L (2016) Carbon dots serve as an effective probe for the quantitative determination and for intracellular imaging of mercury(II). Microchim Acta 183(5):1611–1618
33. Gu D, Shang S, Yu Q, Jie S (2016) Green synthesis of nitrogen-doped carbon dots from lotus root for hg(ii) ions detection and cell imaging. Appl Surf Sci 390:38–42
34. Tang W, Wang Y, Wang P, Di J, Yang J, Wu Y (2016) Synthesis of strongly fluorescent carbon quantum dots modified with polyamidoamine and a triethoxysilane as quenchable fluorescent probes for mercury(II). Microchim Acta 183(9):2571–2578
35. Xu H, Zhang K, Liu Q, Liu Y, Xie M (2017) Visual and fluorescent detection of mercury ions by using a dually emissive ratiometric nanohybrid containing carbon dots and CdTe quantum dots. Microchim Acta. doi:10.1007/s00604-017-2099-1
36. Zhou Y, Ma Z (2016) A novel fluorescence enhanced route to detect copper(II) by click chemistry-catalyzed connection of au@SiO2 and carbon dots. Sensors Actuators B 233:426–430
37. Gedda G, Lee CY, Lin YC, Wu H (2016) Green synthesis of carbon dots from prawn shells for highly selective and sensitive detection of copper ions. Sensors Actuators B 224:396–403
38. Wang L, Bi Y, Gao J, Li Y, Ding H, Ding L (2016) Carbon dots based turn-on fluorescent probes for the sensitive determination of glyphosate in environmental water samples. RSC Adv 6(89): 85820–85828
39. Zhu L, Xu G, Song Q, Tang T, Wang X, Wei F, Hu Q (20160 Highly sensitive determination of dopamine by a turn-on fluorescent biosensor based on aptamer labeled carbon dots and nano-graphite. Sensors Actuators B 231: 506–512
40. Wang B, Chen Y, Wu Y, Weng B, Liu Y, Li CM (2016) Synthesis of nitrogen- and iron-containing carbon dots, and their application to colorimetric and fluorometric determination of dopamine. Microchim Acta 183(9):2491–2500
41. Zuo P, Gao J, Peng J, Liu J, Zhao M, Zhao J, He H (2016) A sol-gel based molecular imprint incorporating carbon dots for fluorometric determination of nicotinic acid. Microchim Acta 183(1):329–336
42. Wang F, Hao Q, Zhang Y, Xu Y, Lei W (2016) Fluorescence quenchometric method for determination of ferric ion using boron-doped carbon dots. Microchim Acta 183(1):273–279
43. Gupta A, Verma NC, Khan S, Tiwari S, Chaudhary A, Nandi CK (2016) Paper strip based and live cell ultrasensitive lead sensor using carbon dots synthesized from biological media. Sensors Actuators B 232:107–114
44. Xiong CY, Liang WB, Wang HJ, Zheng YN, Zhuo Y, Chai YQ, Yuan R (2016) In situ electro-polymerization of nitrogen doped carbon dots and their application in an electrochemiluminescence biosensor for the detection of intracellular lead ions. Chem Comm 52(32):5589–5592
45. Choudhary R, Patra S, Madhuri R, Sharma PK (2016) Equipment-free, single-step, rapid, "on-site" kit for visual detection of lead ions in soil, water, bacteria, live cells, and solid fruits using fluorescent cube-shaped nitrogen-doped carbon dots. ACS Sustain Chem Eng 4(10):5606–5617
46. Liu Y, Zhou Q, Li J, Lei M, Yan X (2016) Selective and sensitive chemosensor for lead ions using fluorescent carbon dots prepared from chocolate by one-step hydrothermal method. Sensors Actuators B 237:597–604
47. Purbia R, Paria S (2016) A simple turn on fluorescent sensor for the selective detection of thiamine using coconut water derived luminescent carbon dots. Biosens Bioelectron 79:467–475
48. Du N, Song J, Li S, Chi YX, Bai FY, Xing YH (2016) A highly stable 3D luminescent indium-polycarboxylic framework for the turn-off detection of UO_2^{2+}, Ru^{3+}, and biomolecule Thiamines. ACS Appl Mater Inter 8(42):1–9
49. Gao Z, Wang L, Su R, Huang R, Qi W, He Z (2015) A carbon dot-based "off-on" fluorescent probe for highly selective and sensitive detection of phytic acid. Biosens Bioelectron 70:232–238
50. Rao H, Liu W, Lu Z, Wang Y, Ge H, Zou P, Wang Y (2016) Silica-coated carbon dots conjugated to CdTe quantum dots: a ratiometric fluorescent probe for copper(II). Microchim Acta 183(2):581–588
51. Agostinho AJ, Souza OW, Anunciação DS, Santos JCC (2016) Simple and sensitive spectrophotometric method for Phytic acid determination in grains. Food Anal Methods 9(7):2087–2096
52. Miao H, Wang L, Zhuo Y, Zhou Z, Yang X (2016) Label-free fluorimetric detection of CEA using carbon dots derived from tomato juice. Biosens Bioelectron 86:83–89
53. Yang Y, Liu Q, Liu Y, Cui J, Liu H, Wang P, Li Y, Chen L, Zhao Z, Dong Y (2017) A novel label-free electrochemical immunosensor based on functionalized nitrogen-doped graphene quantum dots for carcinoembryonic antigen detection. Biosens Bioelectron 90:31–38
54. Guo Y, Yang L, Li W, Wang X, Shang Y, Li B (2016) Carbon dots doped with nitrogen and sulfur and loaded with copper(II) as a "turn-on" fluorescent probe for cystein, glutathione and homocysteine. Microchim Acta 183(4):1409–1416
55. Huang Y, Zhou J, Feng H, Zheng J, Ma HM, Liu W, Tang C, Ao H, Zhao M, Qian Z (2016) A dual-channel fluorescent chemosensor for discriminative detection of glutathione based on functionalized carbon quantum dots. Biosens Bioelectron 86:748–755
56. Ma H, Liu X, Wang X, Li X, Yang C, Iqbal A, Qin W (2017) Sensitive fluorescent light-up probe for enzymatic determination of glucose using carbon dots modified with MnO_2 nanosheets. Microchim Acta 184(1):177–185
57. Cai QY, Li J, Ge J, Zhang L, Hu YL, Li ZH, Qu LB (2015) A rapid fluorescence "switch-on" assay for glutathione detection by using carbon dots-MnO_2 nanocomposites. Biosens Bioelectron 72:31–36
58. Kong D, Yan F, Luo Y, Wang Y, Chen L, Cui F (2016) Carbon nanodots prepared for cellular imaging and turn-on detection of glutathione. Anal Methods 8(23):4736–4743
59. Liu Q, Xu S, Niu C, Li M, He D, Lu Z, Ma L, Na N, Huang F, Jiang H, Ouyang J (2015) Distinguish cancer cells based on targeting turn-on fluorescence imaging by folate functionalized green emitting carbon dots. Biosens Bioelectron 64:119–125
60. Zhang X, Yu Q, He Y, Zhang C, Zhu H, Yang Z, Lu J (2016) Synthesis and biological evaluation of (68) Ga-labeled Pteroyl-Lys conjugates for folate receptor-targeted tumor imaging. J Labelled Compd Rad 59(9):346–353
61. Chen Y, Shang P, Dong Y, Chi Y (2017) Regulating the overlap between the absorption spectrum of metal ion-chromogenic agent and the emission spectrum of carbon-based dots to improve the sensing performance for metal ions. Sensors Actuators B 242: 1210–1215
62. Kong D, Yan F, Han Z, Xu J, Guo X, Chen L (2016) Cobalt(ii) ions detection using carbon dots as an sensitive and selective fluorescent probe. RSC Adv 6(72):67481–67487
63. Thyssen JP, Menne T, Johansen JD, Liden C, Julander A, Moller P, Jellesen MS (2010) A spot test for detection of cobalt release - early experience and findings. Contact Dermatitis 63(2):63–69

64. Barati A, Shamsipur M, Abdollahi H (2016) Metal-ion-mediated fluorescent carbon dots for indirect detection of sulfide ions. Sensors Actuators B 230:289–297
65. Chen J, Li Y, Lv K, Zhong W, Wang H, Wu Z, Yi P, Jiang J (2016) Cyclam-functionalized carbon dots sensor for sensitive and selective detection of copper(II) ion and sulfide anion in aqueous media and its imaging in live cells. Sensors Actuators B 224:298–306
66. Ganiga M, Cyriac J (2016) FRET based ammonia sensor using carbon dots. Sensors Actuators B 225:522–528
67. Mishra SK, Bhardwaj S, Dhar GB (2015) Surface Plasmon resonance-based Fiber optic sensor for the detection of low concentrations of ammonia gas. IEEE Sensors J 15(2):1235–1239
68. Yang C, Deng W, Liu H, Ge S, Yan M (2015) Turn-on fluorescence sensor for glutathione in aqueous solutions using carbon dots–MnO_2 nanocomposites. Sensors Actuators B 216:286–292
69. Qu F, Sun Z, Liu D, Zhao X, You J (2016) Direct and indirect fluorescent detection of tetracyclines using dually emitting carbon dots. Microchim Acta 183(9):2547–2553
70. Shi D, Yan F, Zheng T, Wang Y, Zhou X, Chen L (2015) P-doped carbon dots act as a nanosensor for trace 2,4,6-trinitrophenol detection and a fluorescent reagent for biological imaging. RSC Adv 5(119):98492–98499
71. Campos BB, Contreras-Cáceres R, Bandosz TJ, Jiménez-Jiménez J, Rodríguez-Castellón E, Esteves D, Silva JCG, Algarra M (2016) Carbon dots as fluorescent sensor for detection of explosive nitrocompounds. Carbon 106:171–178
72. Yuan Y, Jiang J, Liu S, Yang J, Zhang H, Yan J, Hu X (2017) Fluorescent carbon dots for glyphosate determination based on fluorescence resonance energy transfer and logic gate operation. Sensors Actuators B 242:545–553
73. Wang Y, Ma T, Ma S, Liu Y, Tian Y, Wang R, Wang J (2017) Fluorometric determination of the antibiotic kanamycin by aptamer-induced FRET quenching and recovery between MoS_2 nanosheets and carbon dots. Microchim Acta 184(1):203–210
74. Xu M, Gao Z, Zhou Q, Lin Y, Lu M, Tang D (2016) Terbium ion-coordinated carbon dots for fluorescent aptasensing of adenosine 5′-triphosphate with unmodified gold nanoparticles. Biosens Bioelectron 86:978–984
75. Wang Y, Zheng J, Zhang Z, Yuan C, Fu D (2009) CdTe nanocrystals as luminescent probes for detecting ATP, folic acid and l-cysteine in aqueous solution. Colloid Surface A 342(1–3): 102–106
76. Zhou SS, Zhang L, Cai QY, Dong ZZ, Geng X, Ge J, Li ZH (2016) A facile label-free aptasensor for detecting ATP based on fluorescence enhancement of poly(thymine)-templated copper nanoparticles. Anal Bioanal Chem 408(24):6711–6717
77. Zhang HY, Wang Y, Xiao S, Wang H, Wang JH, Feng L (2017) Rapid detection of Cr(VI) ions based on cobalt(II)-doped carbon dots. Biosens Bioelectron 87:46–52
78. Chang MMF, Ginjom IR, Ngu-Schwemlein M, Ng SM (2016) Synthesis of yellow fluorescent carbon dots and their application to the determination of chromium(III) with selectivity improved by pH tuning. Microchim Acta 183(6):1899–1907
79. Chen J, Liu J, Li J, Xu L, Qiao Y (2017) One-pot synthesis of nitrogen and sulfur co-doped carbon dots and its application for sensor and multicolor cellular imaging. J Colloid Interf Sci 485: 167–174
80. Huang S, Qiu H, Zhu F, Lu S, Xiao Q (2015) Graphene quantum dots as on-off-on fluorescent probes for chromium(VI) and ascorbic acid. Microchim Acta 182(9–10):1723–1731
81. Pandey I, Kant R (2016) Electrochemical impedance based chiral analysis of anti-ascorbutic drug: l-ascorbic acid and d-ascorbic acid using C-dots decorated conductive polymer nano-composite electrode. Biosens Bioelectron 77:715–724
82. Li L, Wang C, Liu K, Wang Y, Liu K, Lin Y (2015) Hexagonal cobalt oxyhydroxide-carbon dots hybridized surface: high sensitive fluorescence turn-on probe for monitoring of ascorbic acid in rat brain following brain ischemia. Anal Chem 87(6):3404–3411
83. Zou S, Hou C, Fa H, Zhang L, Ma Y, Dong L, Li D, Huo D, Yang M (2017) An efficient fluorescent probe for fluazinam using N, S co-doped carbon dots from l-cysteine. Sensors Actuators B 239:1033–1041
84. Wang Y, Duan YB, Zhou MG (2015) Baseline sensitivity and efficacy of fluazinam in controlling Sclerotinia stem rot of rapeseed. Eur J Plant Pathol 144(2):337–343
85. Barati A, Shamsipur M, Abdollahi H (2015) Hemoglobin detection using carbon dots as a fluorescence probe. Biosens Bioelectron 71: 470–475
86. Li G, Fu H, Chen X, Gong P, Chen G, Xia L, Wang H, You J, Wu Y (2016) Facile and sensitive fluorescence sensing of alkaline phosphatase activity with Photoluminescent carbon dots based on inner filter effect. Anal Chem 88(5):2720–2726
87. Tang C, Qian Z, Huang Y, Xu J, Ao H, Zhao M, Zhou J, Chen J, Feng H (2016) A fluorometric assay for alkaline phosphatase activity based on beta-cyclodextrin-modified carbon quantum dots through host-guest recognition. Biosens Bioelectron 83:274–280
88. Qian ZS, Chai LJ, Huang YY, Tang C, Shen JJ, Chen JR, Feng H (2015) A real-time fluorescent assay for the detection of alkaline phosphatase activity based on carbon quantum dots. Biosens Bioelectron 68:675–680