


 Cite this: *RSC Adv.*, 2022, **12**, 31778

## Photophysics of tetracarboxy-zinc phthalocyanine photosensitizers

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Zinc-tetracarboxy-phthalocyanine (ZnPc(COOH)<sub>4</sub>) was synthesized by a melting method and basic hydrolysis. A ZnPc(COOH)<sub>4</sub>/Fe<sub>3</sub>O<sub>4</sub>/Ch composite was prepared by immobilization of ZnPc(COOH)<sub>4</sub> onto Fe<sub>3</sub>O<sub>4</sub>/chitosan nanoparticles by a simple immersion method. The photophysical properties were studied using UV-vis spectrophotometry, fluorescence spectroscopy and time-correlated single photon counting (TCSPC) in different aqueous solutions. The UV-vis spectra of the ZnPc(COOH)<sub>4</sub>/Fe<sub>3</sub>O<sub>4</sub>/Ch composite displays absorption by the aromatic rings, with a Q band exhibited at λ<sub>max</sub> = 702 nm. Moreover, the ZnPc(COOH)<sub>4</sub>/Fe<sub>3</sub>O<sub>4</sub>/Ch composite exhibits long triplet-state lifetimes of 1.6 μs and 12.3 μs, crucial for application as a photosensitizer. A triplet quantum yield of 0.56 for the ZnPc(COOH)<sub>4</sub>/Fe<sub>3</sub>O<sub>4</sub>/Ch composite in DMSO/H<sub>2</sub>O was achieved. FTIR showed that the conjugation of ZnPc(COOH)<sub>4</sub> with Fe<sub>3</sub>O<sub>4</sub>/chitosan nanoparticles was achieved by electrostatic interaction.

 Received 8th September 2022  
 Accepted 20th October 2022

DOI: 10.1039/d2ra05676c

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### Introduction

Metallophthalocyanine (MPc) derivatives are popular photodynamic therapy (PDT) photosensitizers (PSs). Research on a novel PS requires extensive human effort and a high cost investment over decades before clinical application. Nevertheless, some MPc derivatives, such as: aluminium phthalocyanine (Photosens®, Russia), used against skin, breast and lung malignancies, and cancers of the gastrointestinal tract;<sup>1</sup> silicon Pc (Pc 4, USA), for the sterilization of blood components against human colon, breast and ovarian cancers, and gliomas;<sup>2</sup> and a liposomal zinc phthalocyanine formulation, using a controlled organic solvent dilution against squamous cell carcinomas of the upper aerodigestive tract,<sup>3</sup> have undergone clinical trials.

Current efforts are being made in the development of new photosensitizers (PSs) with improved solubility in body fluids and injectable solvents, photostability, enhanced permeability and retention effect, elimination and cumulative systemic toxicity.<sup>4–9</sup> In the field of organic photosensitizers, metallophthalocyanines (MPcs) play an important role due to their excellent photo- and electro-chemical stability and exclusive light-harvesting capability in the red/NIR spectral regions.<sup>10–13</sup>

The main disadvantages of MPcs in PDT are the lack of solubility and selectivity; therefore, the combination of magnetic iron oxide nanoparticles with a photosensitizer is a new and promising approach in PDT. Fe<sub>3</sub>O<sub>4</sub> nanoparticles

have been successfully applied in tumor therapy by inducing hyperthermia and oxidative stress that lead to tumor cell damage.<sup>14–16</sup> For application in PDT, magnetic nanoparticles (NPs) are usually coated with polymers, bound to the particle through organic linkers.<sup>17</sup> Functionalization of Fe<sub>3</sub>O<sub>4</sub> nanoparticles may lead to enhancement of their biocompatibility, colloidal stability, and an increase in the number of groups, through which the required antitumor effect can be obtained.

The major goal of this paper is to create a new photosensitizer with adequate solubility, especially in body fluids and injectable solvents, with greater tumor selectivity, enhanced hydrophilicity, and strong absorption in the NIR spectral region. Therefore, conjugation of an MPc derivative to a magnetic NP functionalized with a polymer is the first part of our research aimed at delivering PSs to tumor cells. The magnetic iron oxide nanoparticles will be used as the carrier of the photosensitizer because of: their ability to carry and deliver therapeutic photosensitizers into deep-seated tumours; the enhanced solubility of the hydrophobic PS with an appropriate size to accumulate in the tumour tissues *via* enhanced permeability and retention effect; and the ability to attack cancer cells selectively without harming other healthy cells. The Fe<sub>3</sub>O<sub>4</sub> NPs will be functionalized with chitosan, which is a biodegradable, biocompatible polysaccharide and, in comparison with many other polymers, has many free –OH and –NH<sub>2</sub> groups that can serve as anchors for conjugation of therapeutics and targeting ligands.

Considering the above mentioned information, we focused our research on attaching functionalized ZnPc with carboxylic groups (–COOH) to an Fe<sub>3</sub>O<sub>4</sub>/chitosan system hoping to get a synergistic effect in the photodynamic parameters of the resulting composite.

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## Materials and methods

### Materials

All materials, trimellitic anhydride, zinc acetate dehydrate ( $\text{Zn}(\text{CH}_3\text{COOH})_2 \cdot 2\text{H}_2\text{O}$ ), ammonium molybdate tetrahydrate ( $(\text{NH}_4)_6\text{MO}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$ ), anhydrous sodium sulfate ( $\text{Na}_2\text{SO}_4$ ), urea, 1-bromo-naphthalene, hydrochloric acid and acetic acid were purchased from Sigma-Aldrich, Inc., St. Louis, MO, USA and used as received. Dimethyl sulfoxide (DMSO), chitosan (Ch) and hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) were obtained from Alfa Aesar, Heysham, UK.  $\text{Fe}_3\text{O}_4$  nanoparticles (Merck) were cleaned in a flux of hydrogen at room temperature for 20 minutes.

### Equipment

The UV-vis spectra of the solutions were measured using a UV-vis spectrophotometer (Lambda 25, PerkinElmer, Inc., Shelton, CT, USA) from 200 nm to 1200 nm in 10 mm quartz cuvettes. The steady-state fluorescence spectroscopy was performed using a spectrometer (LS-55, PerkinElmer, Inc., Shelton, CT, USA) equipped with double-grating excitation and emission monochromators. Time-correlated single photon counting (TCSPC) was used to determine the fluorescence lifetime. The time-resolved fluorescence spectra were recorded on a spectrometer (FLS980, Edinburgh Instruments, Livingston EH54 7DQ, Oxford, UK). All the measurements were made at room temperature ( $295 \pm 1$  K). A Bruker D8 ADVANCE X-ray diffractometer (using  $\text{Cu K}_\alpha$  radiation with  $\lambda = 1.5406 \text{ \AA}$ ) was used for structural investigation of the magnetic nanoparticles. A Bruker FTIR spectrometer was used to provide information about the chemical composition.

## Synthesis

### The synthetic pathway of $\text{ZnPc}(\text{COOH})_4$

A mixture consisting of 4.35 g (0.022 mol) of trimellitic anhydride, 2.52 g of  $\text{Zn}(\text{CH}_3\text{COOH})_2 \cdot 2\text{H}_2\text{O}$ , 0.3 g of  $(\text{NH}_4)_6\text{MO}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$ , 0.5 g of  $\text{Na}_2\text{SO}_4$ , 13.51 g (0.225 mol) of urea and 5 ml of 1-bromonaphthalene was heated at 200–205 °C for 8 h with continuous stirring. After 8 hours, the reaction mixture was cooled to room temperature and treated with methanol. The obtained suspension was filtered. The solid reaction product was washed on the filter with methanol, chloroform and, finally, with acetone. After drying, the product was crumbled and then refluxed for one hour in 5% hydrochloric acid (HCl) solution. After drying, the same procedure was carried out with 5% sodium hydroxide (NaOH) solution for one hour at 90 °C. Finally, the solution was acidified with HCl until the pH was equal to 2, and the precipitated final product was filtered and dried in the open air. 0.68 g of  $\text{ZnPc}(\text{COOH})_4$  was obtained with a yield of 70% (Fig. 1).

### Preparation of chitosan-functionalized magnetic nanoparticles

Chitosan and  $\text{Fe}_3\text{O}_4$  were mixed in an appropriate proportion to form the chitosan-magnetic nanoparticles composite with amine groups by the reverse-phase suspension cross-linking

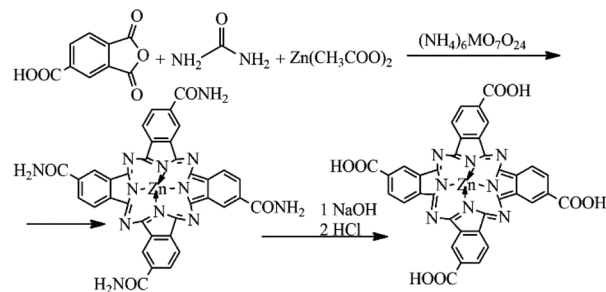


Fig. 1 Schematic diagram of  $\text{ZnPc}(\text{COOH})_4$  synthesis.

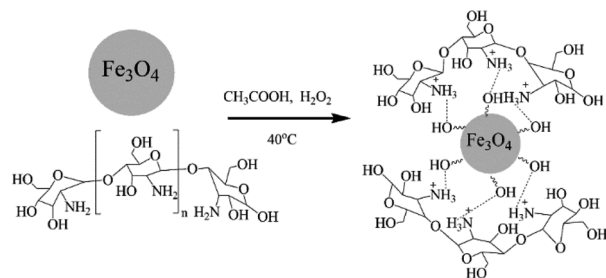


Fig. 2 Schematic diagram of the preparation of chitosan-functionalized magnetic nanoparticles.

method.<sup>18</sup> Aqueous acetic acid solution was used as a solvent for the chitosan polymer and  $\text{H}_2\text{O}_2$  was used as the cross-linker. In this specific procedure, a chitosan solution was prepared using a mixture of 2% acetic acid and 10%  $\text{H}_2\text{O}_2$  solutions. Then 0.2 g  $\text{Fe}_3\text{O}_4$  was added and stirred with strong ultrasonic agitation at room temperature for 4 h. At the end of this period, some of the chitosan- $\text{Fe}_3\text{O}_4$  nanocomposite particles were collected from the reaction mixture by using a permanent magnet. The product was washed with ethanol and dried in vacuum at 60 °C for 5 hours and used for XRD analysis (Fig. 2).

Chitosan is able to interact with negatively charged molecules,<sup>19</sup> such as the hydroxyl ( $\text{Fe}-\text{OH}$ ) groups on the surface of magnetite nanoparticles. The presence of  $-\text{OH}$  groups on the surface of the  $\text{Fe}_3\text{O}_4$  nanoparticles was confirmed by the strong broad band with a maximum at  $3431 \text{ cm}^{-1}$  in the IR spectrum (Fig. 4), corresponding to  $\nu(\text{O}-\text{H})$  oscillations. We suppose that ionic interactions occur between the negatively charged  $\text{CH}_3\text{COO}^-$  species and the positively charged ( $\text{NH}_3^+$ ) groups of the chitosan molecules dissolved in the aqueous acetic acid solution.

### The conjugation of $\text{ZnPc}(\text{COOH})_4$ to chitosan, $\text{Fe}_3\text{O}_4$ and $\text{Fe}_3\text{O}_4/\text{Ch}$ nanoparticles

Acetic acid is a weak acid and is a very common solvent for chitosan. A sample of 0.3 g of chitosan was dissolved in 50 ml of 2% concentrated acetic acid. Then 0.5 ml of 10% hydrogen peroxide was added to the solution for the destruction of intermacromolecular hydrogen bonds and interchain hydrogen bonds to make water-soluble chitosan. The appropriate ratio of chitosan to acetic acid in the chitosan-acetic acid solution was



1 : 0.5, and then  $\text{ZnPc}(\text{COOH})_4$  was dissolved in a 1 : 1 DMSO/ $\text{H}_2\text{O}$  solution. After that, both solutions were mixed, heated at 40 °C and stirred continuously for 40 min.

In a separate experiment,  $\text{ZnPc}(\text{COOH})_4$  solution was mixed with a dispersion medium containing chitosan-functionalized magnetic nanoparticles at room temperature and stirred for 2 h using a mechanical stirrer.

Experiments where  $\text{ZnPc}(\text{COOH})_4$  was dissolved in 1 : 1 DMSO/ $\text{H}_2\text{O}$  solution and simply mixed with  $\text{Fe}_3\text{O}_4$  were also performed.

## Results and discussion

### Structural analysis of the $\text{Fe}_3\text{O}_4$ and $\text{Fe}_3\text{O}_4$ /chitosan magnetic nanoparticles

The X-ray diffraction patterns of the  $\text{Fe}_3\text{O}_4$  and  $\text{Fe}_3\text{O}_4$ /chitosan nanoparticles, along with the standard pattern of  $\text{Fe}_3\text{O}_4$  (JCPDS #75-0033), are shown in Fig. 3 and details of the peaks are given in Table 1. The similar XRD patterns reveal that  $\text{Fe}_3\text{O}_4$  does not undergo any phase changes following functionalization with chitosan, a situation also confirmed by other reports.<sup>20,21</sup>

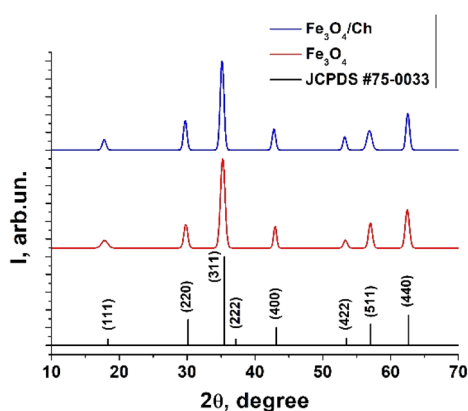


Fig. 3 XRD patterns of the  $\text{Fe}_3\text{O}_4$  and  $\text{Fe}_3\text{O}_4$ /chitosan nanoparticles, and the JCPDS #75-0033 card.

Table 1 Structural parameters of the  $\text{Fe}_3\text{O}_4$  and  $\text{Fe}_3\text{O}_4$ /chitosan nanoparticles

	$2\theta$	FWHM	$D$ , nm	$D_{\text{mean}}$ , nm
$\text{Fe}_3\text{O}_4$	17.84	1.05	8.5	13.95
	29.81	0.67	13.7	
	35.25	0.79	11.	
	42.99	0.52	18.1	
	53.35	0.62	15.9	
	57.03	0.66	15.3	
	62.47	0.72	14.3	
	62.54	0.61	16.8	
$\text{Fe}_3\text{O}_4/\text{Ch}$	17.78	0.66	13.5	14.80
	29.72	0.61	15.0	
	35.16	0.66	14.1	
	42.81	0.60	15.8	
	53.24	0.59	16.7	
	56.88	0.86	11.7	
	62.54	0.61	16.8	

XRD diffraction analysis revealed a broad nature of the diffraction maxima, indicating that  $\text{Fe}_3\text{O}_4$  has small crystallite sizes. The crystallite sizes were evaluated using the Debye-Scherrer formula:

$$D = (k\lambda/\beta \cos \theta) \quad (1)$$

where  $\lambda$  is the wavelength of the X-rays (1.5406 Å),  $\beta$  is the FWHM (full width at half maximum),  $\theta$  is the diffraction angle,  $k = 0.94$  and  $D$  is the crystallite size. The metal oxide nanoparticles have a mean crystallite size of 13.95 nm. During the coating process with chitosan, the crystallite size slightly increases, as the size of the individual crystallite is related to the thickness of the chitosan layer. The mean crystallite size of the nanoparticles with chitosan increases up to 14.80 nm.

### FTIR analysis

The FTIR spectra of chitosan, the  $\text{Fe}_3\text{O}_4$  and  $\text{Fe}_3\text{O}_4$ /chitosan nanoparticles,  $\text{ZnPc}(\text{COOH})_4$  and the  $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4$ /chitosan composite are presented in Fig. 4 and 5. The intense peak observed at 636  $\text{cm}^{-1}$  in the FTIR spectrum of  $\text{Fe}_3\text{O}_4$  is attributed to the stretching vibration mode associated with Fe–O bonds in the crystalline lattice of the  $\text{Fe}_3\text{O}_4$  nanoparticles. This

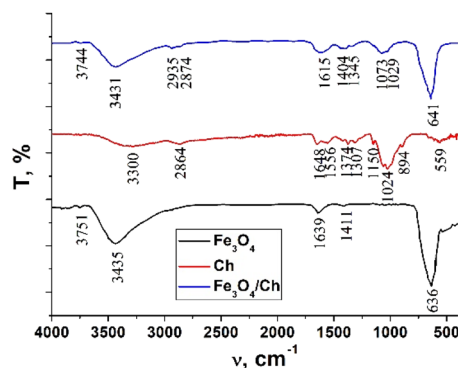


Fig. 4 FTIR spectra of chitosan, the  $\text{Fe}_3\text{O}_4$  nanoparticles and the  $\text{Fe}_3\text{O}_4$ /chitosan nanoparticles.

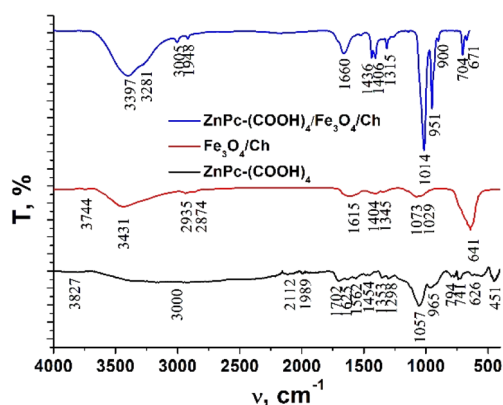


Fig. 5 FTIR spectra of  $\text{ZnPc}(\text{COOH})_4$ ,  $\text{Fe}_3\text{O}_4$ /chitosan and the  $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4$ /chitosan composite.



vibration is shifted to  $641\text{ cm}^{-1}$  in the FTIR spectrum of the  $\text{Fe}_3\text{O}_4$ /chitosan nanoparticles. The modification and shift of the main characteristic bands (stretching C–O at  $1024\text{ cm}^{-1}$ , bending  $\text{NH}_2$  at  $1648\text{ cm}^{-1}$ , stretching O–H  $3300\text{ cm}^{-1}$  and C–H  $2864\text{ cm}^{-1}$ ) in the IR spectrum of chitosan to  $1073$  and  $1029\text{ cm}^{-1}$  ( $\nu(\text{C–O})$ ),  $1615\text{ cm}^{-1}$  ( $\delta(\text{NH}_2)$ ),  $3431\text{ cm}^{-1}$  ( $\nu(\text{O–H})$ ), and  $2935$  and  $2874\text{ cm}^{-1}$  ( $\nu(\text{C–H})$ ) in the IR spectrum of the  $\text{Fe}_3\text{O}_4$ /chitosan system demonstrate the binding of chitosan to the  $\text{Fe}_3\text{O}_4$  nanoparticles (Fig. 4). The result is consistent with similar investigations.<sup>22,23</sup> The chemical interaction of  $\text{ZnPc}(\text{COOH})_4$  with the  $\text{Fe}_3\text{O}_4$ /chitosan system is confirmed by the shift of the signal from  $1702\text{ cm}^{-1}$  ( $\nu(\text{C=O})$ ) of the protonated COOH groups in the IR spectrum of  $\text{ZnPc}(\text{COOH})_4$ , associated with splitting, to  $1660\text{ cm}^{-1}$  ( $\nu_{\text{sym}}(\text{COO})$ ), and  $1436$  and  $1406\text{ cm}^{-1}$  ( $\nu_{\text{asym}}(\text{COO})$ ) that correspond to deprotonated carboxylic groups. This can be explained by the dissociation of carboxylic groups and formation of electrostatic interactions between  $\text{NH}_3^+$  and  $\text{COO}^-$  fragments (Fig. 16a).

### UV-vis and fluorescence analysis

Usually, MPcs give rise to electronic spectra with two strong absorption bands, one around  $300\text{ nm}$ , called the “B” or Soret band, due to electronic transitions from the deeper  $\pi$ -HOMO to  $n^*$ -LUMO energy levels, while the other at  $600$ – $650\text{ nm}$ , called the “Q” band, due to electronic transitions from the  $\pi$ -HOMO to  $\pi^*$ -LUMO energy levels.<sup>24</sup> The UV-vis spectra of  $\text{ZnPc}(\text{COOH})_4$  and  $\text{ZnPc}(\text{COOH})_4/\text{Ch}$  in  $\text{DMSO}/\text{H}_2\text{O}$  are presented in Fig. 6. The absorption spectra of the synthesized materials display absorption peaks in the visible region at around  $700\text{ nm}$ . In the case of  $\text{ZnPc}(\text{COOH})_4$  and  $\text{ZnPc}(\text{COOH})_4/\text{Ch}$  dissolved in  $\text{DMSO}/\text{H}_2\text{O}$ , absorption maxima are situated at  $640$  and  $697\text{ nm}$ , and  $642$  and  $699\text{ nm}$ , respectively. The shifts of the Q band depend on the change in electron distribution in the phthalocyanine ring caused by the substituents and their position. The UV-vis spectra of  $\text{ZnPc}(\text{COOH})_4$  immobilized on non-functionalized magnetic nanoparticles are shown in Fig. 7. The intensity of the absorption for the  $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4$  material in a solution of  $1:1:2$   $\text{DMSO}/\text{Ac.ac}/\text{phys.sol.}$  (where “Ac.ac” is acetic acid, and “phys.sol.” is a physiological NaCl solution) decreases when decreasing the molar concentration of  $\text{ZnPc}(\text{COOH})_4$  from

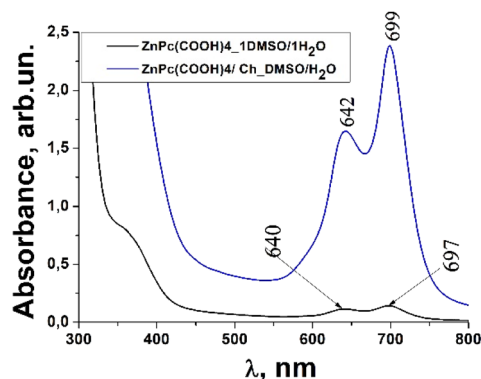


Fig. 6 Absorbance spectra changes of the  $\text{ZnPc}(\text{COOH})_4$  compound and  $\text{ZnPc}(\text{COOH})_4/\text{Ch}$  in  $\text{DMSO}/\text{H}_2\text{O}$  solvent.

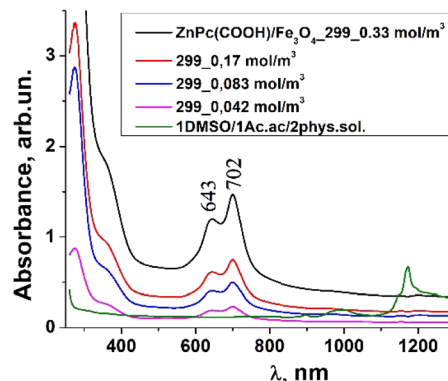


Fig. 7 Absorbance spectra changes of  $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4$  in  $\text{DMSO}/\text{Ac.ac}/\text{phys.sol.}$  solution,  $1:1:2$  ratio, at different molar concentrations.

$0.33\text{ mol m}^{-3}$  to  $0.042\text{ mol m}^{-3}$ . The conjugation of  $\text{ZnPc}(\text{COOH})_4$  with the chitosan-functionalized  $\text{Fe}_3\text{O}_4$  nanoparticles gives rise to similar positions of the maxima in the Q band absorbance spectra (Fig. 8) as in the case when  $\text{ZnPc}(\text{COOH})_4$  is mixed with the non-functionalized  $\text{Fe}_3\text{O}_4$  nanoparticles. A difference appears in the width of the bands, with a narrower band being found for  $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4/\text{Ch}$  than for  $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4$ .

In Fig. 7,  $\text{Fe}_3\text{O}_4$  was dissolved in a physiological solution of  $0.9\%$  NaCl and  $2\%$  acetic acid. For the  $\text{Fe}_3\text{O}_4$ /chitosan solution measurements shown in Fig. 8,  $2\%$  acetic acid and  $10\%$  hydrogen peroxide were used. The Q band extends into the  $580$ – $800\text{ nm}$  region and exhibited two peaks at  $\lambda_{\text{max}} = 645\text{ nm}$  and  $702\text{ nm}$  in the case of the  $\text{Fe}_3\text{O}_4$  nanoparticles linked to chitosan (Fig. 8), almost the same values as when  $\text{Fe}_3\text{O}_4$  is not bound to chitosan (Fig. 7). Both the  $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4/\text{chitosan}$  and  $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4$  spectra (Fig. 9) show similar specific absorption peaks of the phthalocyanine aromatic ring. The chitosan had no obvious absorption peak in the visible region, but leads to an increased intensity of the  $702\text{ nm}$  peak and a narrower Q band. The comparison in Fig. 9 allows us to suppose that the Q absorption band could be assigned to the  $\pi$ -

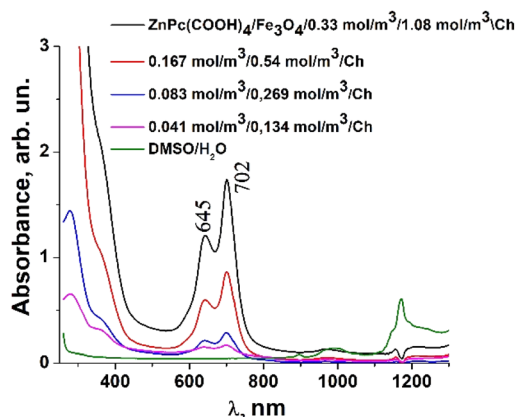


Fig. 8 Absorbance of the  $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4/\text{Ch}$  composite in  $\text{DMSO}/\text{H}_2\text{O}$  solution at different molar concentrations.





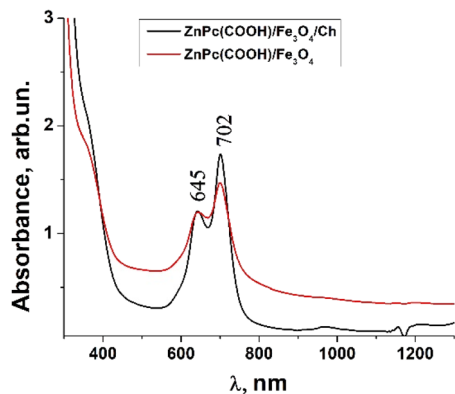


Fig. 9 Comparison of the absorbance of the  $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4$  and  $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4/\text{Ch}$  composites in DMSO/phys.sol. 0.9% and DMSO/ $\text{H}_2\text{O}_2/\text{Ac.ac}$  solutions.

$\pi^*$  transition on the ZnPc macrocycle. Introducing the peripheral  $-\text{COOH}$  substituent onto the macrocycle of ZnPc led to a significant bathochromic shift of the absorption spectra due to an increased destabilization of the HOMO electron state versus the LUMO state.

The low energy peak is due to the monomer, while the high energy peak is caused by the aggregation. The aggregation

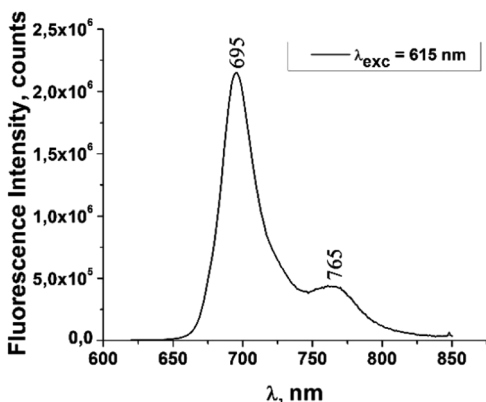


Fig. 10 Emission spectrum of  $\text{ZnPc}(\text{COOH})_4$  in DMSO/ $\text{H}_2\text{O}$  solution.

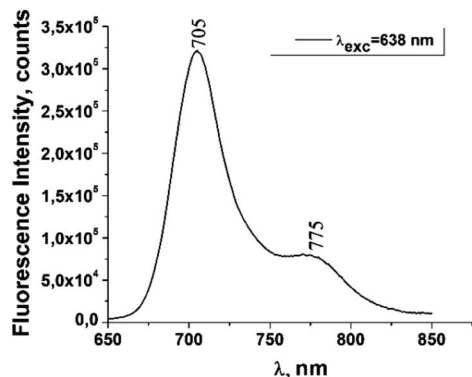


Fig. 11 Emission spectrum of  $\text{ZnPc}(\text{COOH})_4/\text{chitosan}$  in DMSO/ $\text{H}_2\text{O}$  solution.

species persisted more when the  $\text{Fe}_3\text{O}_4$  nanoparticles were not bound to chitosan.

The fluorescence emission spectrum of  $\text{ZnPc}(\text{COOH})_4$  in DMSO/ $\text{H}_2\text{O}$  is shown in Fig. 10. The fluorescence spectrum after excitation at 615 nm shows two emission bands situated at 695 nm and 765 nm. The fluorescence spectrum of the  $\text{ZnPc}(\text{COOH})_4/\text{chitosan}$  system (Fig. 11) after excitation at 638 nm also shows two bands, as in Fig. 10, but they are both shifted 10 nm into the near-infrared region. The fluorescence

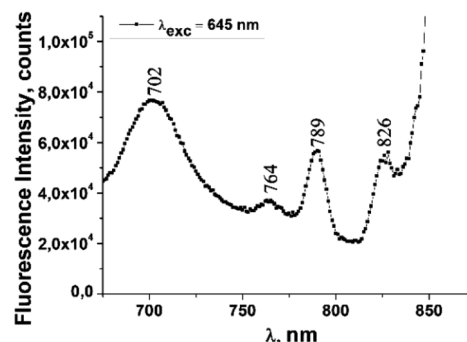


Fig. 12 Emission spectrum of  $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4$  in DMSO/phys.-sol. 0.9% solution.

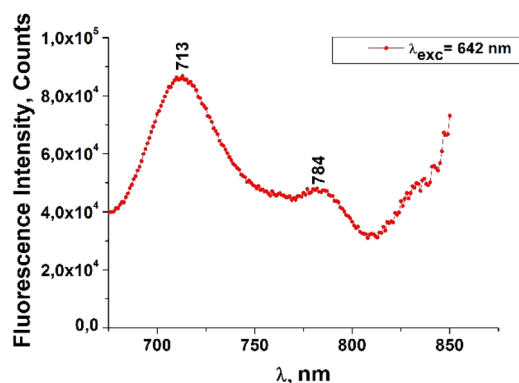


Fig. 13 Emission spectrum of  $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4/\text{chitosan}$  in DMSO/ $\text{H}_2\text{O}_2/\text{Ac.ac}$  solution.

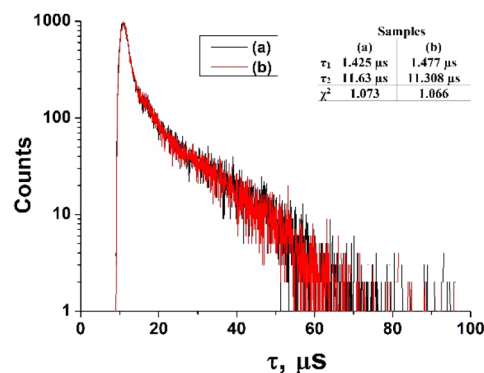


Fig. 14 The fluorescence lifetimes of  $\text{ZnPc}(\text{COOH})_4$  (a) and  $\text{ZnPc}(\text{COOH})_4/\text{chitosan}$  (b) in DMSO/ $\text{H}_2\text{O}$  solution.



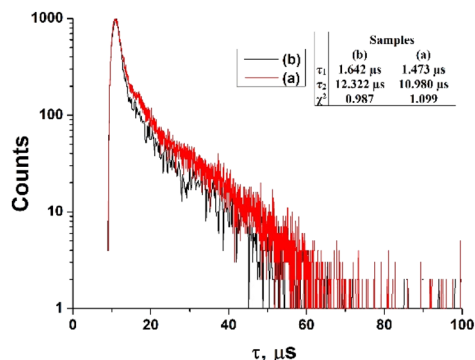


Fig. 15 The fluorescence lifetimes of ZnPc(COOH)<sub>4</sub>/Fe<sub>3</sub>O<sub>4</sub> in DMSO/phys.sol. 0.9% (a) and ZnPc(COOH)<sub>4</sub>/Fe<sub>3</sub>O<sub>4</sub>/chitosan in DMSO/H<sub>2</sub>O<sub>2</sub>/Ac.ac (b) solutions.

spectrum of ZnPc(COOH)<sub>4</sub> immobilized on the Fe<sub>3</sub>O<sub>4</sub> magnetic nanoparticles shows broad and structured fluorescence at 702 nm, 764 nm, 789 nm and 826 nm, and shows an increase in intensity at 850 nm, when excited at 645 nm (Fig. 12). The limits of the measurement equipment did not allow us to record fluorescence above 850 nm. The spectrum of ZnPc(COOH)<sub>4</sub> immobilized on the Fe<sub>3</sub>O<sub>4</sub>/chitosan magnetic nanoparticles shown in

Fig. 13 displayed less structured fluorescence. Only two broad bands situated at 713 nm and 784 nm shifted to the near-infrared region are revealed. The resultant red-shift was associated with the electrostatic interaction between ZnPc(COOH)<sub>4</sub> and the chitosan-functionalized Fe<sub>3</sub>O<sub>4</sub> nanoparticles.

The fluorescence lifetimes of ZnPc(COOH)<sub>4</sub> and ZnPc(COOH)<sub>4</sub>/chitosan in DMSO/H<sub>2</sub>O solution are presented in Fig. 14.

The fluorescence decays of ZnPc(COOH)<sub>4</sub> and ZnPc(COOH)<sub>4</sub>/chitosan in DMSO/H<sub>2</sub>O solutions at about the same interval of excitation wavelengths ( $\lambda_{\text{exc}} = 684\text{--}772$  nm) show a bi-exponential behaviour with lifetime values being 1.42  $\mu\text{s}$  and 11.63  $\mu\text{s}$  for the solution without chitosan, while, for the solution with chitosan, values of 1.47  $\mu\text{s}$  and 11.31  $\mu\text{s}$  are reported. The presence of chitosan does not induce significant variations in the fluorescence decay times. Thus, because the NH<sub>2</sub> groups in chitosan can form the same ionic bonds with the COOH groups, even in the absence of Fe<sub>3</sub>O<sub>4</sub>, but only in the presence of Fe<sub>3</sub>O<sub>4</sub>, the fluorescence decay time changes. So, the presence of Fe<sub>3</sub>O<sub>4</sub> NPs is vital for the main result of the chemical reactions of the developed composite.

In Fig. 15, the fluorescence lifetimes of ZnPc(COOH)<sub>4</sub>/Fe<sub>3</sub>O<sub>4</sub> and ZnPc(COOH)<sub>4</sub>/Fe<sub>3</sub>O<sub>4</sub>/chitosan in DMSO/phys.sol. 0.9% and DMSO/H<sub>2</sub>O<sub>2</sub>/Ac.ac solutions are illustrated. The fluorescence

Table 2 Photophysical parameters: triplet quantum yields ( $\Phi_T$ ) and the triplet-state lifetimes ( $\tau_T$ ) for all compounds

	Solvent	$\lambda_{\text{abs}}$ , nm	$\lambda_{\text{emis}}$ , nm	$\Phi_T$	$\tau_T$ , $\mu\text{s}$
ZnPc(COOH) <sub>4</sub>	DMSO/H <sub>2</sub> O	697	765	0.25	11.63
ZnPc(COOH) <sub>4</sub> /chitosan	DMSO/H <sub>2</sub> O	699	775	0.27	11.31
ZnPc(COOH) <sub>4</sub> /Fe <sub>3</sub> O <sub>4</sub>	DMSO/phys.sol. 0.9%	702	826	0.23	10.98
ZnPc(COOH) <sub>4</sub> /Fe <sub>3</sub> O <sub>4</sub> /chitosan	DMSO/H <sub>2</sub> O <sub>2</sub> /Ac.ac	702	784	0.56	12.32

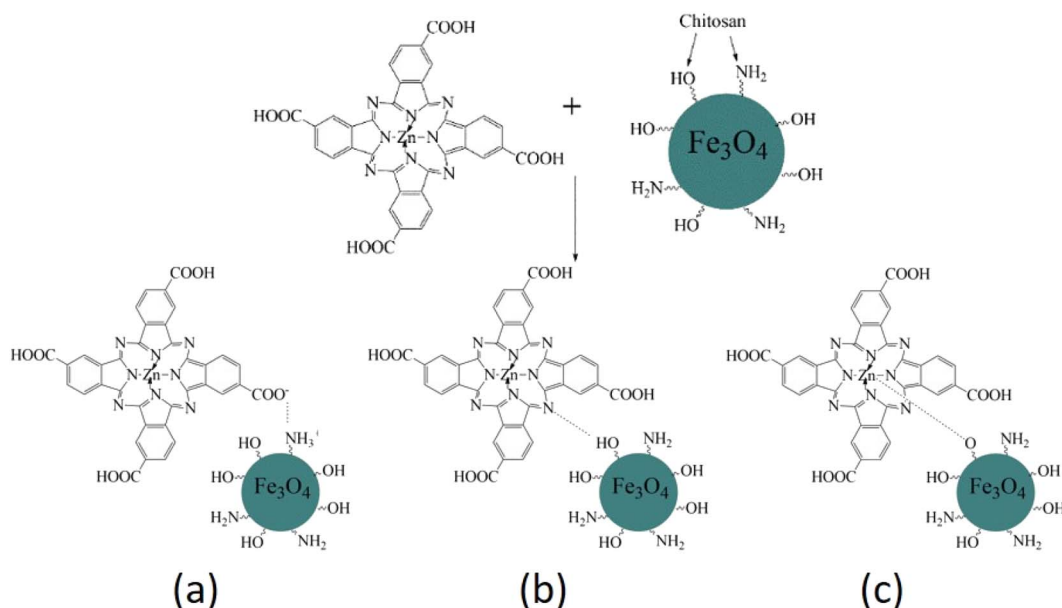


Fig. 16 Scheme of the possible interactions (electrostatic (a), hydrogen (b) and coordination bonds (c)) of ZnPc(COOH)<sub>4</sub> with the chitosan-functionalized Fe<sub>3</sub>O<sub>4</sub> nanoparticles.



decay curve for  $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4$  yielded two lifetimes of 1.47  $\mu\text{s}$  and 10.98  $\mu\text{s}$ . The values are smaller than those of the  $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4/\text{chitosan}$  composite, although the contribution of the shorter lifetime component is less than 13%. The longer lifetime in the  $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4/\text{chitosan}$  composite can be explained by the magnetic nanoparticles' functionalization with chitosan. The fluorescence quantum yield values of the  $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4$  or  $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4/\text{chitosan}$  composites in DMSO/phys.sol. 0.9% and DMSO/ $\text{H}_2\text{O}_2/\text{Ac.ac}$  solutions of 1 : 1 ratio were found to be lower than that for non-substituted  $\text{ZnPc}$  in non-diluted DMSO (0.67 in ref. 25) due to increased intersystem crossing in the presence of the  $\text{Fe}_3\text{O}_4$  NPs. The photophysical parameters: triplet ( $\Phi_T$ ) quantum yields and the triplet-state lifetimes ( $\tau_T$ ), for  $\text{ZnPc}(\text{COOH})_4$  linked to magnetic nanoparticles are presented in Table 2.

So, we suppose that the surface interaction between the amino groups of the chitosan/ $\text{Fe}_3\text{O}_4$  and the carboxylic groups of  $\text{ZnPc}(\text{COOH})_4$  most probably forms an electrostatic interaction. In addition to the electrostatic interaction between charged surfaces of  $\text{ZnPc}(\text{COOH})_4$  and chitosan/ $\text{Fe}_3\text{O}_4$ , coordination bonds between the  $\text{Zn}^{2+}$  ions of phthalocyanine and the oxygen atoms of chitosan/ $\text{Fe}_3\text{O}_4$  can be formed.<sup>26,27</sup> Also, hydrogen bonds between the nitrogen atoms of phthalocyanine and the hydrogen atoms of chitosan/ $\text{Fe}_3\text{O}_4$  are also possible, as shown in the scheme presented in Fig. 16.

So, significant efforts have been made to develop the  $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4/\text{chitosan}$  composite that has strong absorption of long-wavelength light and a triplet quantum yield of 0.56 that can be promising for PDT. But further studies will continue to improve the triplet-state lifetime and the triplet quantum yield, and elucidate the physicochemical processes in this composite. Moreover, *in vitro* and *in vivo* studies are required to elucidate the PDT effects.

## Conclusions

In this study we have developed:

(1) a soluble  $\text{ZnPc}(\text{COOH})_4$  photosensitizer in DMSO/ $\text{H}_2\text{O}$ , ratio 1 : 1, with high absorption at 702 nm, excitation/emission wavelengths of 615/765 nm and fluorescence lifetimes of 1.42  $\mu\text{s}$  and 11.63  $\mu\text{s}$ .

(2)  $\text{Fe}_3\text{O}_4/\text{chitosan}$  magnetic nanoparticles with a mean crystallite size of the nanoparticles up 14.80 nm using the suspension cross-linking technique.

(3)  $\text{ZnPc}(\text{COOH})_4$  immobilized on chitosan-functionalized  $\text{Fe}_3\text{O}_4$  nanoparticles through an immersion method with the aid of DMSO/ $\text{H}_2\text{O}_2/\text{Ac.ac}$  solution, exhibits higher triplet lifetimes of 1.6  $\mu\text{s}$  and 12.3  $\mu\text{s}$ .

The values of the triplet quantum yield (0.56) and the triplet-state lifetimes of  $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4/\text{Ch}$  make this composite a promising candidate for PDT.

## Author contributions

Conceptualization: T. Potlog, S. Robu and I. Bulimestru; methodology: A. Popusoi and S. Robu; formal analysis: A. Popusoi; investigation: I. Lungu and A. Popusoi; data curation: A.

Popusoi and I. Lungu; writing – original draft preparation: T. Potlog and S. Robu; writing – review and editing: I. Bulimestru, T. Potlog and S. Robu; supervision: T. Potlog. All authors have read and agreed to the published version of the manuscript.

## Conflicts of interest

The authors declare no conflict of interest.

## Acknowledgements

This research was supported by the 20.80009.5007.16 project of the Ministry of Education and Research of the Republic of Moldova. Also, profound thanks and appreciation to Research4Life.

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