



Control and sorting of inhomogeneous dielectric core-shell nanoparticles using two counter-propagating plane waves

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Abstract Many typical nanoscale structures consist of dielectric nanoparticles with an inevitable oxide-generated coating around them. Depending on the fabrication techniques and the intended purposes, these coatings may not be homogeneous, and their distortion can cause advantages or disadvantages in the applications of such systems. Based on finite element simulations, inhomogeneous core-shell nanoparticle systems are numerically studied when illuminated with two counter-propagating plane waves in the optical range. It is found that the electromagnetic field distortions caused by the inhomogeneous system under Mie resonance conditions allow the system to exhibit controllable one-directional impulsion and rotation, which mainly depends on the offset between the core and shell. The overall geometry and composition of the system also dictate the type of resonance being excited. Overall, this “photonic thruster” effect consisting of an accelerating and spinning projectile would provide stability to particle movement and additionally establish a method to distinguish inhomogeneous from homogeneous particles. The method can be scaled to a wide range of nanoscale dielectric particles. Thus, the results are useful for detecting defects in nanosystems with a simple concept and may open avenues for improving nanoparticle synthesis methods.

1 Introduction

The ability to manipulate matter with light is nowadays an accessible tool since many applications have proven to be extremely useful, like microscopy [1–4], light sail development [5], living cells’ characterization, manipulation, and surgery [6–11], microrheology [12, 13], cancer theragnosis [9, 14], cooling of gases by laser radiation [15, 16], tracking of bacteriae and viruses [17], and remote sampling [18], along with others.

On the other hand, the core-shell nanoparticle systems have become essential in the nanoscale for several reasons. They can serve as multifunctional sensors or smart drug-delivery vehicles in biology and medicine [19]. They can be regarded as a simplified form of metamaterials, as they combine two or more materials with distinct properties within hybrid nanoparticles, thus offering the potential to enhance or customize their characteristics [20, 21]. Protecting the core/s with shell layers that may even be incompatible with each other is one of the best advantages of this type of structures over the others [22]. Currently, precise synthesis methods can imbue these nanoparticles with highly advantageous properties such as thermal stability, solubility, and low toxicity [21–23]. Consequently, these attributes render the particles suitable for a wide range of applications, including drug delivery and detection [21], bioimaging, sensors [24, 25], solar cell development, removal of heavy metals [22], and surface modification [23], to name just a few.

In particular, the use of dielectric core-shell nanoparticles can represent specific advantages over their counterparts due to simple reasons [23, 24]. For example, dielectric nanoparticles can support electric and magnetic volumetric resonances (Mie resonances) [26, 27], which involve hot spots within the materials at their lowest energy modes [28], especially when high-dielectric contrast materials are used. This is distinct from nanosystems that support surface resonances like surface plasmons, which create hot spots near tips or surfaces, potentially making the particles invasive in their surroundings [29, 30]. Consequently, an appropriate design of dielectric coated particles can lead to lower energy loss than designs using metallic nanoparticles. For instance, the dielectric function of the shell layer can be optimized for the miniaturization of dielectric capacitors in electronic and electrical systems [25, 26]. Dielectric particles can also exhibit enhanced high-index sensitivity for sensing applications [27]. Even a variety of natural systems like a living cell or active matter can sometimes be conceived as dielectric core-shell systems [28, 29].

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However, although many core–shell nanoparticle types are on demand [30–33], the precise control of the particle fabrication is still far from being achieved. For example, the yolk–shell structure has recently shown excellent physical and chemical properties, thus showing great potential in many fields, such as lithium-ion batteries, drug delivery, nanoreactors, and catalysis [34, 35]. This sort of structure can even represent particles with movable or isolated cores to gain some flexibility, including volume expansion. Nonetheless, this and many other kinds of complex core–shell systems may present deficient ripening processes or undesirable final structures, thus failing their application purposes [36]. Moreover, the healing of structures with defects has become an active research field to improve the efficiency of fabrication methods, especially those based on ripening processes or techniques involving dramatic volume change that eventually leads to particle fracture [34, 37]. On the other hand, breakable shells can become also essential [38]. Therefore, core–shell flexible designs with controllable inhomogeneities allow for multifield sensing or mass/energy storage for industrially scalable products [20, 39].

In this regard, efficient separation or sorting methods are essential for the development of manipulation of nanoscale devices required for high demand manufacturing purposes. Many classes of procedures have been established for particle sorting, a few involving complex physical–chemical processes [21, 40, 41]. Others are based on purely physical phenomena, such as optical forces. [12, 42–44]. However, most of these methods become difficult to apply because they involve heavy-duty instruments, or lack control of monodispersity, stability, repetitiveness, or result economically inviable [20, 30, 31, 33, 45].

In this work, a method to sort core–shell nanoparticles is presented based on the resonant properties of dielectric systems and the symmetry breaking that occurs when there are defects in the particles, like inhomogeneous shells. In a previous study documented in Ref. [12], the rotation induced in eccentric particles of the core–shell type was explored, using an approximation for a propagating Gaussian beam as the source of illumination. However, in the present case, a different methodology is proposed, which uses an incident beam consisting of two circularly-polarized optical waves propagating in opposite directions with equal circular polarization. This method offers a clear advantage, as the high symmetry imposed by the beam along the propagation axis makes the fields scattered by the core–shell system sensitive to geometric symmetry-breaking phenomena like shell nonuniformity. This property provides valuable information about the system's dynamics.

Specifically, the current numerical study focuses on a silicon core and a silica shell, which can arise as a by-product of core oxidation [46–48]. Silicon is usually regarded as one of the best core materials in core–shell structures for energy storage [34]. In addition, its optical properties (high contrast) make it suitable for the excitation of both electric and magnetic resonances [49]. On the other hand, the results presented in this article remain general and independent of the particles' size, specific geometry, and constitution, as long as the particle's Mie resonances are identified and high-contrast dielectrics are used. Moreover, this paper explores a set of sizes and presents a notable result: a net propulsion effect and rotation when inhomogeneous core–shell particles are present in the sample. Exhaustive exploration and optimization of the induced force by modifying beam shapes, wavelengths, or different surrounding media is considered out of the scope of this paper, as well as studies concerning the realistic dynamics of the particle.

2 Methods

Figure 1 shows the geometry under study. Two counter-propagating plane waves of the same handedness, namely, left-handed circular polarization (LCP), constitute the incident field along the $\pm z$ -axis upon the system, in such a way that the electric field is given by:

$$\vec{E}_0 = \frac{E_0}{2} \left[(\tilde{x} + i\tilde{y})e^{ik_0z} + (\tilde{x} - i\tilde{y})e^{-ik_0z} \right] \quad (1)$$

This choice presents particular characteristics for the time-average in the incident field's dynamic variables. For instance, the average momentum and spin density result both zero [50, 51], whereas that the total energy and the helicity density are constants in general different than zero [52].

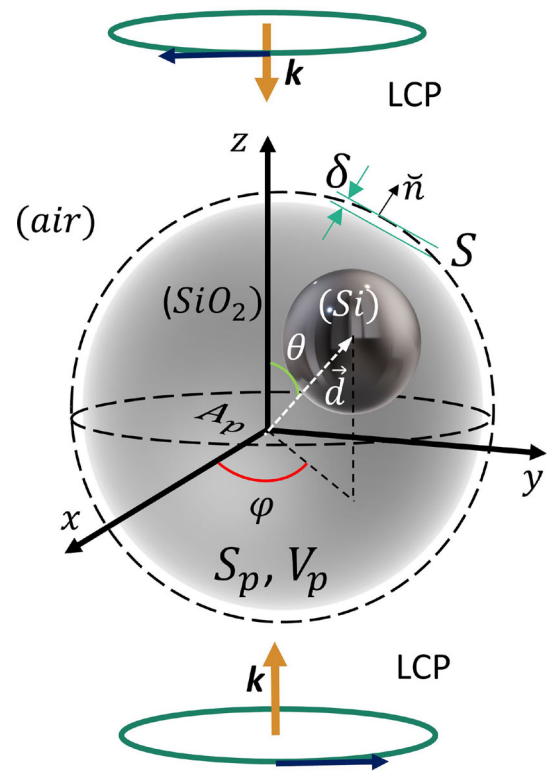
The scatterer is a nanoparticle with a silicon core (Si) and a silica shell (SiO₂), which is immersed in air and whose core is in the displaced position $\vec{d}$ (see Fig. 1). $\vec{d}$ can also be characterized by the angles and radius defined in spherical coordinates, i.e., (d, φ, θ) . In Fig. 1, the circle in dashed line that surrounds the particle represents a surface S , whose normal versor is $\vec{n}$. Note that $S \rightarrow S_p$ when $\delta \rightarrow 0$, where S_p is the particle surface. The following dimensionless definitions are calculated from the total electromagnetic fields which are solution of the problem,

$$Q_{abs} = \frac{4}{A_p c \omega_E^{tot}} \int_{V_p} \text{Re} \left\{ \vec{J} \cdot \vec{E}^* - i \omega \vec{B} \cdot \vec{H}^* \right\} dV, \quad (2)$$

$$Q_{sca} = \frac{4}{A_p c \omega_E^{tot}} \oint_{S_p} \text{Re} \left\{ \vec{E}_{sca} \times \vec{H}_{sca}^* \right\} \cdot \vec{n} ds, \quad (3)$$

where Q_{abs} and Q_{sca} are the optical efficiencies for the particle in vacuum, $\omega_E^{tot} = \varepsilon_0 |\vec{E}_0|^2$ is the total electric energy density of the illumination, V_p is the particle volume, and A_p is the area of the particle which is transversal to the illumination (see Fig. 1, dashed

Fig. 1 (Color online) Definition of geometry, materials, and illumination configuration. The offset's distance and angles are defined by the vector $\vec{d}$, following the usual spherical coordinate system. The spherical surface S tends to the particle's surface S_p when $\delta \rightarrow 0$. The area transversal to the illumination is A_p



circle in perspective when $\delta \rightarrow 0$). The total time-averaged force $\langle \vec{F} \rangle$ and torque $\langle \vec{N} \rangle$ exerted on the particle can be calculated using the surface integrals,

$$\langle \vec{F} \rangle = \frac{1}{2} \oint_S \text{Re} \{ \vec{T} \cdot \vec{n} \} ds, \quad (4)$$

$$\langle \vec{N} \rangle = \frac{1}{2} \oint_S \text{Re} \{ \langle (\vec{r} - \vec{r}_0) \times \vec{T} \rangle \cdot \vec{n} \} ds, \quad (5)$$

where $\langle \vec{T} \rangle$ is the time-averaged Maxwell stress tensor (MST), whose form for time-harmonic fields is given explicitly by

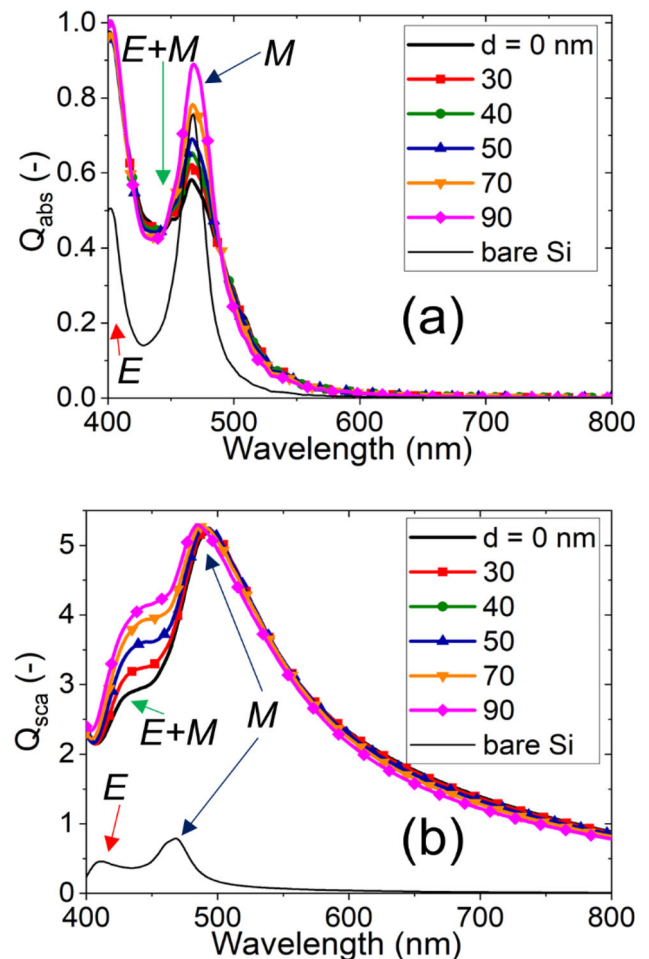
$$\langle \vec{T} \rangle = \epsilon_0 \overline{\vec{E}} \otimes \overline{\vec{E}} + \mu_0 \overline{\vec{H}} \otimes \overline{\vec{H}} - \frac{1}{2} (\epsilon_0 |\overline{\vec{E}}|^2 + \mu_0 |\overline{\vec{H}}|^2) \vec{I}, \quad (6)$$

where $\otimes$ is the outer product and $\vec{I}$ is the unit tensor. In the torque, $\vec{r}_0$ is the reference point. The total electromagnetic fields $\vec{E}$, $\vec{B}$, $\vec{H}$, (incident plus scattered), scattered fields $\vec{E}_{sca}$, $\vec{H}_{sca}$, and their conjugates were calculated by simulations based on a finite element method (FEM). This FEM model was built into COMSOL MULTIPHYSICS 6.2 (details in Ref. [53]). Specifically, three regions were assumed for the host, shell, and core medium as indicated in Fig. 1. A perfectly matched layer was added in combination with a scattering boundary condition to effectively model an infinite host medium that avoids back reflections (not drawn for simplicity). To ensure convergence, an unstructured tetrahedral mesh was used with a maximum mesh size of one-tenth of the minimum distance between the core and shell boundaries of the system. For the torque calculations, the center of mass (CM) of the structure was chosen as $\vec{r}_0$.

3 Results and discussion

The discussion centers around a main illustrative example for a 300 nm particle with a 100 nm core ($r_1=150$, $r_2=50$ nm) and then briefly extends to other ranges in the nanoscale. The characteristic spectra of optical efficiencies are discussed in (3.1). Then, the study deals with core offsets parallel to the illumination axis (z-axis), where a resonant “thruster” effect is obtained, see (3.2). A broader discussion about arbitrary offset directions for a particular offset value is made in (3.3). After that, a brief discussion follows about the physical origin of the optomechanical phenomena (3.4). Finally, the study of (3.2) is extended in subsection (3.5) to include the radiation pressure at other nanoscale particle sizes. To predict the dynamics of the particle, the particle is assumed as

Fig. 2 (Color online) Spectra of optical efficiencies for several offset values. **a**, **b** absorption [scattering]. Black solid [thin] line for the homogeneous shell (zero offset) [bare silicon]. E and M labels indicate the electric and magnetic dipolar resonances derived from near fields around the silicon core. The label E + M means a hybrid resonance due to the overlapping between E and M modes and the core–shell coupling



“quasistatic,” i.e., it is moving with almost zero velocity and acceleration. This is a valid approximation for incident fields with low intensities and serves as a first approximation to the system dynamics [54].

3.1 Optical behavior: efficiencies

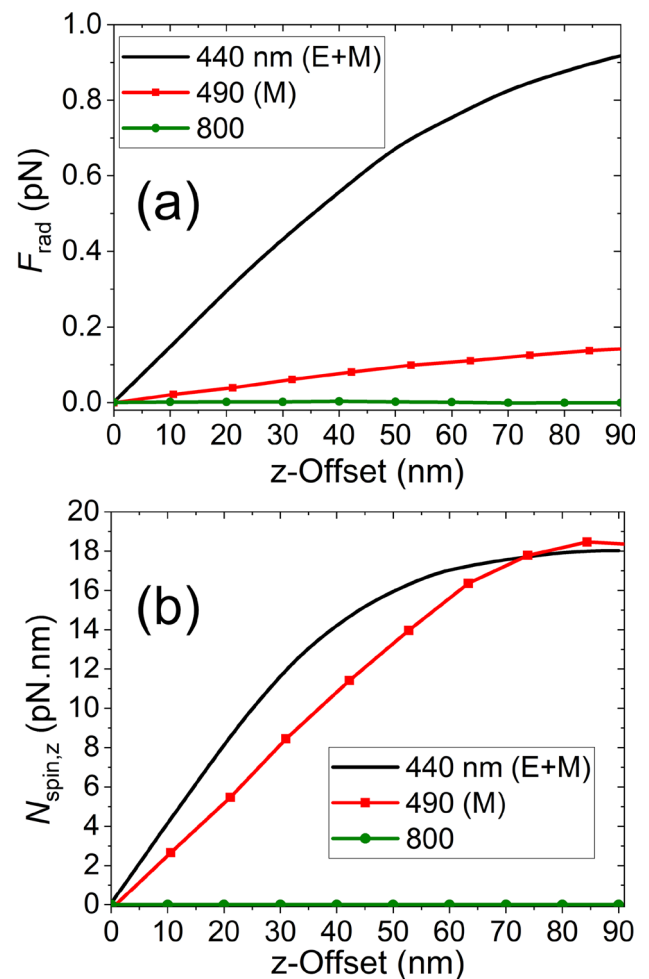
Figure 2a, b shows the spectra of absorption [scattering] efficiency for several values of the offset magnitude along the z direction. Black thick [thin] line corresponds to a concentric core–shell system [bare core]. Note that the response varies their optical intensities, but almost no resonance shifts occur. The nature of these Mie resonances can be deduced from an analysis of the curves for a bare core and the behavior of the near fields (not shown for brevity) [55]. It is verified that just two volume modes appear in the studied optical range for the chosen parameters. The lowest energy (longest wavelength) mode corresponds to the magnetic dipole (M), while the highest energy (shortest wavelength) is the electric mode (E). Despite this classification, when the core is surrounded by the SiO_2 shell, a kind of hybrid mode (labeled E + M in Fig. 2) appears between the M and E modes, though the overlapping of these latter is strong and mask the new resonance, especially in the absorption.

Although the efficiencies indeed respond to the system’s perturbation, such as the presence of a core–shell offset, they are not enough to completely characterize the system nor identify in which direction the offset is located, especially under symmetric illumination conditions (see Fig. 1). Nevertheless, the mechanical inductions on the particle are expected to contain more details about the perturbation because it uses the near fields [49, 56, 57].

3.2 Resonant “thruster” effect for parallel offsets

As the two optical modes labeled E + M and M could be more sensitive to the offset’s variation, Fig. 3 shows the z -components of the forces and torques exerted on inhomogenous particles as a function of the offset along z for three wavelength locations, namely, 440 nm (resonance E + M mode), 490 nm (resonance M), and 800 nm, this latter constituting an out-of-resonance example. Due to the symmetry, no other components appear for this example. Intriguingly, a net radiation force ($F_{rad} \equiv \langle F_z \rangle$, Fig. 3a) and torque with respect to the CM ($N_{spin,z} \equiv \langle N_z \rangle$, b) appear due to the multiple interactions between the core and shell as soon as the offset ceases

Fig. 3 (Color online) Force (a) and Torque (b) as a function of the offset (d) along z for three different wavelengths: electric (E) and magnetic (M) resonances, and a nonresonant wavelength at 800 nm. The wavelength locations of the resonances correspond approximately to those for Q_{sca} in Fig. 2b



to be zero. As can be seen from the curves, the phenomenon is resonant: it is practically zero out of resonance and increases as the intensity of the resonance increases. Moreover, this net force results proportional to the offset distance from the particle's center. In particular, there is a crossing point between the curves for 440 and 490 nm for the torque (Fig. 3b) so that the maximum is achieved for the highest possible value of offset under M resonance.

Note that both mechanical reactions occur simultaneously and in a preferential direction since the offset is assumed in the positive z -axis. This “thruster” phenomenon provides the particle with both propulsion and spin, therefore self-stabilizing its movement as in a rocket system. Remarkably, this effect represents a potential detection mechanism for identifying inconsistencies in particle fabrication. The particle itself will be compelled to move and spin in the same direction as that of its anomaly, akin to how they behave in a velocity–mass selector.

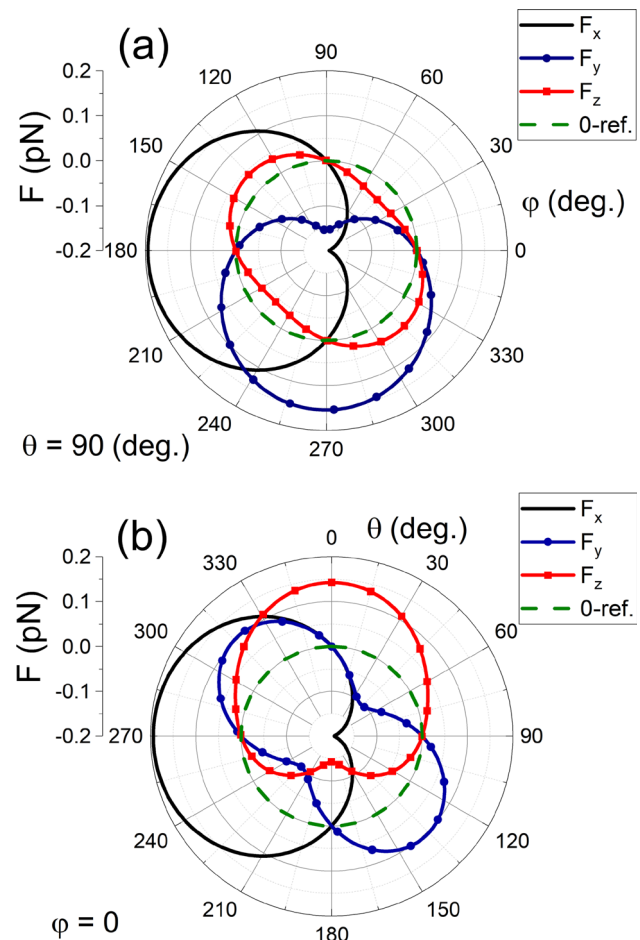
As a complement of the presented study, a video file can be found in the SM that represents the distribution of tangential forces around the particle when d is varied along the z direction (Figure S1). The reader may find in the SM more details and discussion about this complex phenomenon.

Following the study, a natural question arises: How will the particle move if it is arbitrarily oriented with its anomaly in a direction different from the illumination's? This is the subject of the next subsection. In sub Sects. 3.3–3.5, the study focuses on the case for M resonance.

3.3 Mechanical predictions for arbitrary offsets.

To help visualize the phenomena, Figs. 4 and 5 show polar plots for the net forces and torques exerted on the particle for $d = 90$ nm. For simplicity, results from two planes are given; panels (a) track the resultant contributions along the x – y plane while φ varies around the particle's equator (i.e., $\theta = 90^\circ$, see Fig. 4). Panels (b) describe a transversal variation as a function of θ around the plane $\varphi = 0^\circ$ (x – z plane, Fig. 4). Besides the three components in each case, a zero reference is highlighted in green dashed line. Note that maxima and minima exist for each line since the patterns are anisotropic. From Fig. 4a, it turns out that the force exerted on

Fig. 4 Polar plots of the components of the net force for several angles θ and φ . The offset is $d=90$ nm. The wavelength corresponds to the magnetic resonance for an average np; 490 nm. **a** Force distribution as a function of φ around the equator, i.e., for $\theta = 90$ deg. **b** Idem as a function of θ around the plane $\varphi = 0$ deg



the particle tries to reorient the particle anomaly toward the origin of the x - y plane; if such force is expressed as $\vec{F}_{(x,y)} = F_r \vec{r} + F_\varphi \vec{\varphi}$, the radial force becomes $-|F_r| \vec{r}$ at $\varphi = 0, 90, 180, 270$ deg while F_z is zero at these points. However, these points of relative maximum for the force's absolute value are unstable; small perturbations can cause non-negligible forces to appear along the z -axis, which will take the CM out of the x - y plane. On the other hand, as the polar angle θ of the CM approaches the z -axis (either 0 or 180 degrees), the F_z component will increase until it reaches their extremes when the CM is located parallel or counter parallel to the z -axis (Fig. 4b). The system preserves the cylindrical symmetry of the illumination; however, the force distribution when the core moves around the particle's CM is not straightforward to address.

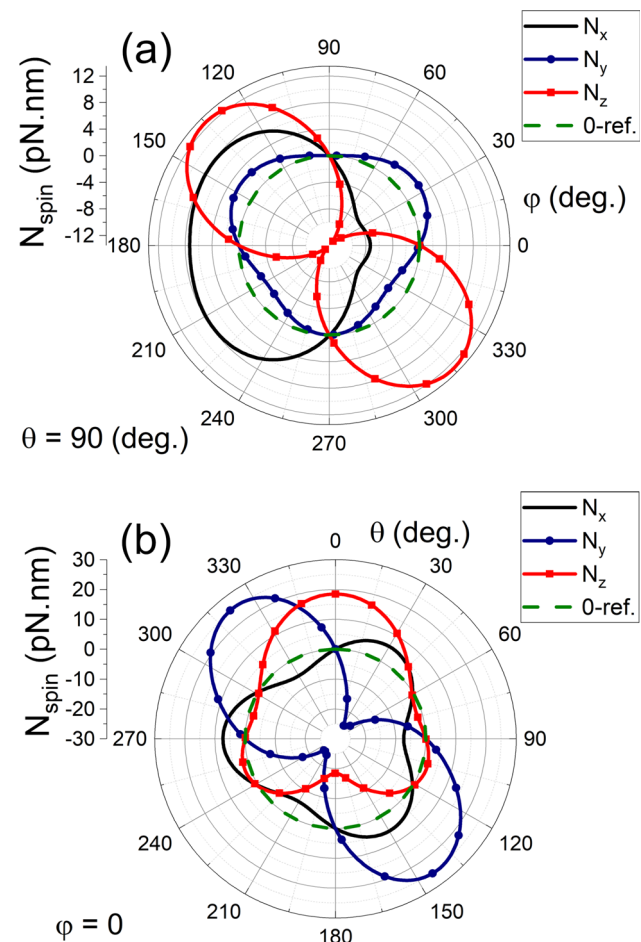
Now the discussion moves to spin torques, Fig. 5. Torques can be considered another representation for the tangential forces around the CM, as will be analyzed below. The torque curves present an even more complex behavior. In general, note that both N_y and N_z are zero along the directions $\varphi = 0, 90, 180, 270$ deg when $\theta = 90$ deg, Fig. 5a; N_x presents their extremes for $\varphi = 0, 180$ deg. Remarkably, the torque/spin aligns with the force along the x and z directions; in other words, N_x [N_z] points to the origin together with F_x [F_z], Fig. 4a and Fig. 5a [4b and 5b]. Curiously, F_y has a cardioid pattern which is shifted with respect to that for F_x and like this latter, but both distributions are not equal, compare the black solid line with the blue line + circles in Fig. 4a.

It is evident that from Figs. 4 and 5 that a certain angle, namely, 135 deg. remains preferential in both angles θ and φ . This direction presents the maximum values for the spin torque, $N_z(\varphi)$ [$N_y(\theta)$] in the case of Fig. 5a, b. N_y 's maximum practically doubles N_z 's. When the CM aligns with the z -axis, the torque has a component only in the z direction. This angle appears because the induced fields are sensitive to the helical shape of the incident field, as will be explained below.

As a complement of the presented study, two video files can be found in the SM that represent the distribution of tangential forces around the particle at M resonance for $d = 95$ nm, namely, $\theta = 90$ deg while φ is varied, and $\varphi = 0$ deg while θ is varied, Figs. S2 and S3.

From Fig. 4b, note another exceptional feature of the induced z -force, see red line with circles: those core positions above [below] the plane $z = 0$ imply a positive [negative] radiation force, thus following the orientation of the anomaly. In a cluster of *dispersed* particles, this phenomenon would allow, in principle, a clear separation of homogeneous particles, namely, particles with perfect shells, from anomalous ones. This conclusion is supported by complementary studies involving arbitrary directions for the core, which can be found in the SM.

Fig. 5 Idem Fig. 4 for the spin torque (angular torque distributions)



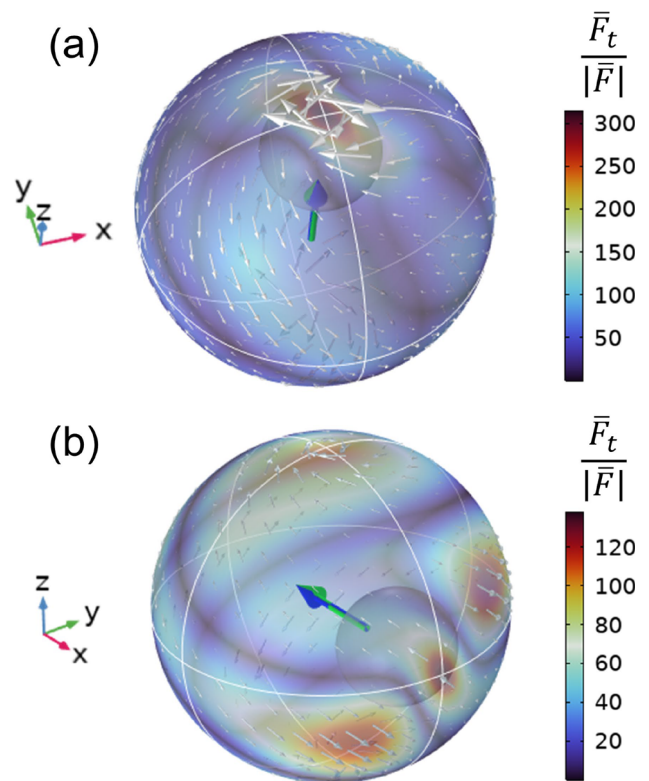
To illustrate more on the behavior of the mechanical variables when a perturbation is present, Fig. 6 depicts the distribution of tangential forces for a case $d = 95$ nm, which resonates nearly at 490 nm. Panel (a) corresponds to an offset along z , and (b) idem along x , showing the phenomenon of transverse net force described above. In both cases, the net force (blue central arrow) is parallel to the net torque (green central arrow). To highlight the direction of these vectors, their scale is increased 100 times. The color scale represents the magnitude of the forces and the white arrows the tangential force field around the particle's surface. In both cases, there are clear induction effects due to the proximity of the core to the particle's surface. The maxima for the spots are close to the minimum distance between core and shell, though the case in panel (b) presents a more complex shape because the azimuthal symmetry of the system is broken. Although the distributions are quite intricate, they follow the helical shape of the incident field along the particle's extension (though the wavelength is larger than the particle). This means that the mechanical variables are very sensitive to the electromagnetic fields and are reliable observables of the system, contrary to the conventional assumption that all the fields' information can be extracted from the optical efficiencies or any other similar far-field observable. The reason why there is a leaned angle of about 135° in Figs. 4 and 5 is due to the shape of the incident field.

Up to this point, we can summarize that, in principle, a diluted set of inhomogeneous particles illuminated by the light field proposed in the current method will be forced to move along the axis defined by the direction of propagation of such incident waves. The particles will be accelerated in this direction and rotate around its CM, providing stability. Brownian motion and viscosity strongly perturb the dynamics in a more realistic scenario. Random collisions, in combination with viscosity, would alter the particle's linear and angular accelerations by means of external forces and torques. However, the induced forces would have an unbalanced component in the direction of propagation of the incident beams. Therefore, on average, particles with eccentricities are expected to migrate along that axis.

3.4 Physical origin of the phenomena

It was reported that the mechanical magnitudes such as the induced forces and torques would depend on more fundamental dynamic variables than can be observables of the electromagnetic fields associated [51, 52, 58]. With the aim to show about the origin of the presented unconventional forces and torques, Fig. 7 explores the behavior of the scalar densities that are characteristic of

Fig. 6 (Color online) Distribution of tangential forces around the particle's outer surface, which is used to calculate the forces using the MST formulation given in Eq. (4). The field, in white arrows, is scaled to the total force's magnitude by a factor of 0.24. The colormaps correspond to the magnitude of the tangential forces scaled to the total force's magnitude. The blue and green arrows correspond, respectively, to the net forces and torques, but their scale is increased 100 times for better visualization. The offset is $d=95$ nm. The wavelength corresponds to the magnetic resonance for an average nanoparticle; 490 nm. (a) For a z-offset, (b) for an x-offset ($\varphi = 0$, $\theta = 90$ deg)



the particle-field dynamics of the system. Figure 7a, b displays, respectively, the absolute value of the electric and magnetic spin densities, while Fig. 7c presents the helicity density. All panels correspond to the case $d=95$ nm along the z-axis for the M resonance at 490 nm. As a result of the multiple scattering between the core and the shell, all the variables indicate anisotropic distributions when scaled appropriately using the incident field's magnitudes. Logically, the magnetic density is enhanced when compared to its electric counterpart, since the resonance excited is magnetic. On the other hand, the magnetic density is more localized inside the particle because the magnetic-field spot is focused on the core region (not shown here). The electric field spreads more across the shell region so the induced spots in Fig. 7a–c clearly reach the outer particle's surface. It is worth mentioning that these variables are non-negligible when $d = 0$; however, all the distributions are highly symmetric in that case and their spots balanced so that there is no net preferential direction, and no asymmetric mechanics exist (not shown for brevity).

3.5 Variation of the radiation pressure with the size. Study of the size dependence.

Finally, with the aim to complete a parametric study, let us vary the size of the system beyond the example 100–300 nm when the offset d is kept again along the z-axis. For conciseness, the results correspond to a set of particles with geometric similarity, as follows. If the minimum distance δ between core and shell is defined as $\delta = R_b - R_a - d$, where R_a , R_b are, respectively, the core and shell radii, the scales $\delta/2R_a$ and $\delta/2R_b$ are kept constant while varying the particle's size.

The line shown in Fig. 8 corresponds to the radiation pressure (F_z) exerted on the particle as a function of the magnetic resonance wavelength (M wavelength, vertical axis) and δ (horizontal axis). The analysis of the torques is avoided for simplicity. The line points are obtained by getting the maximum of the spectra of forces at the location of the M dipolar resonance, or lowest energy mode, since several multipolar resonances are excited when the particle size increases. Noticeably, a linear trend is obtained as δ varies, which would help identify the particles or calibrate the device if the method of particle separation were applied.

Note that no resonance appears below the value $\delta = 10$ nm, provided that such a small core cannot support Mie resonances of volume type as to continue the trend of geometric-similar systems. In any case, smaller values of δ would result in unrealistic since nonlocal corrections to the constitutive parameters are likely to appear due to quantum effects.

4 Conclusion

A method of detection of particle anomalies/particle sorting is proposed from a simple optical illumination by taking profit of the resonant properties of dielectric core-shell nanoparticles. In a broad range of nanoparticle sizes, the lowest energy volumetric Mie resonances induce strong anisotropic mechanical inductions on the whole particle, such as unbalanced radiation pressure and particle

Fig. 7 Behavior of the fundamental, scalar, dynamic densities for the electromagnetic field induced in the system. The offset is $d=95$ nm along the z-axis. The wavelength corresponds to the magnetic resonance for an average nanoparticle; 490 nm. **(a)** Spin **(b)** helicity. **(a)** Electric and **(b)** magnetic, respectively. The quantities are scaled by the appropriate magnitudes of the incident field

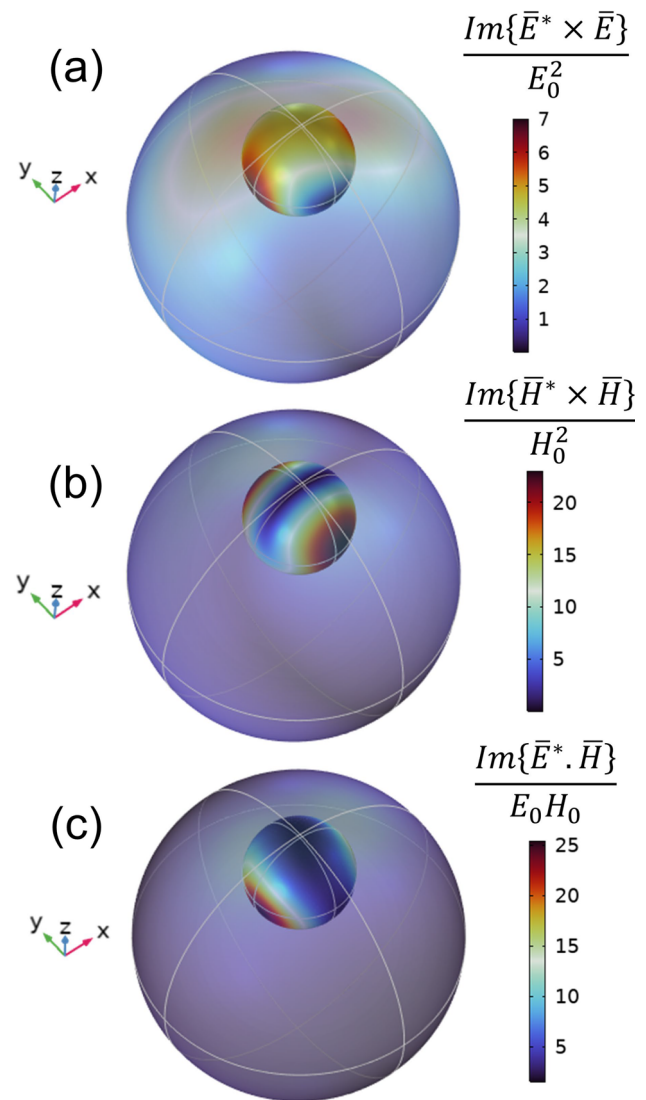
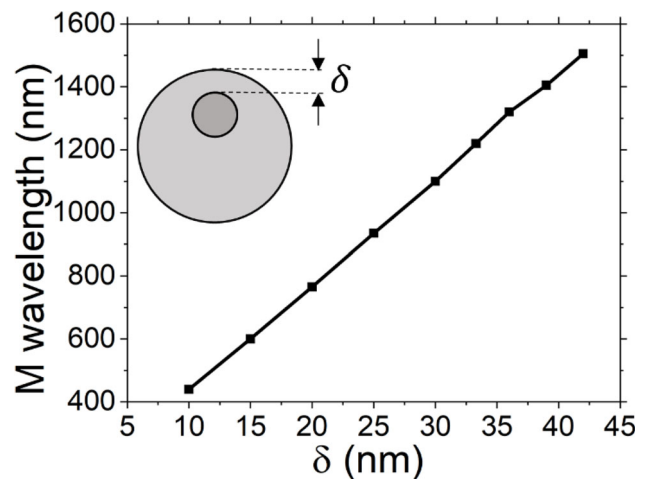


Fig. 8 (Color online) Study of the radiation force exerted on the particle as a function of the size for particles with geometrical similarity. The black line is the location of the lowest energy magnetic resonance (labeled as M wavelength, vertical axis) as a function of the minimum distance between the core and the shell, δ (horizontal axis)



rotations. These results are based on the symmetry breaking produced by inhomogeneous shells under symmetric illumination, the “shape” of the incident field, and the high-contrast material present. The symmetry breaking induces anisotropic forces from the electromagnetic interaction between the core and the shell of the system, and these forces increase in magnitude with the dielectric contrast used. In particular, the mechanical variables carry the information of that interaction through their dependence on the near

fields. Remarkably, the relatively strong dipolar magnetic resonance (lowest energy mode) sets an acceptable linear dependence of the optomechanics on the size of the particles, which allows for complete particle discrimination from inhomogeneous to homogenous shells. Specifically, Figs. 3, 4, 5, and 8 can help define novel particle sorting models. As the forces induced also grow with increase in offset values for a fixed size, the concept is capable in principle to distinguish degrees of anomalies in a range of values for the eccentricity. The fact that torques also arise from the induction would also matter in other applications different from particle selectors such, for instance, nanoprinting, nanoscale measurements of viscosity, and light sail propulsion, among others.

Although the addition of experimental results is considered beyond the scope of our paper, we strongly encourage the community to begin designing experiments to support the current theoretical findings.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1140/epjp/s13360-025-06053-1>.

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Data Availability Statement The data that support the findings of this study are available upon reasonable request from the authors.

Declarations

Conflict of interest The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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