



**UNIVERSIDAD NACIONAL AUTÓNOMA DE MÉXICO
POSGRADO EN CIENCIAS FÍSICAS**

**OPTICAL RESPONSE OF PARTIALLY EMBEDDED
NANOSPHERES**

**TESIS
QUE PARA OPTAR POR EL GRADO DE:
MAESTRO EN CIENCIAS (FÍSICA)**

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CIUDAD DE MÉXICO, MÉXICO, 2021

Abstract/Resumen

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Background and Motivation

It is recommended to fill in this part of the document with the following information:

Metasurfaces are bidimensional arrays of unit cells with geometrical dimensions smaller than the wavelength of the incident light. Biosensing-aimed metasurfaces are supported onto a substrate and immersed in an aqueous medium, thus its performance is limited by its washability. One alternative to decrease a metasurface's washability is to partially embed it within the substrate while allowing the metasurface to still interact with the aqueous medium. In this work, we study the optical response of a single partially embedded metallic nanosphere and extend its behavior analytically into a disordered metasurface by employing an effective medium approach.

The incrustation of the metasurface is studied by calculating the spectral behavior of a single partially embedded nanosphere with the Finite Element Method (FEM) and proposing an effective polarizability in the elements of the metasurface.

- Your field: Context about the field your are working
Plasmonics -> Metamaterials -> Biosensing
- Motivation: Backgroung about your thesis work and why did you choose this project and why is it important.
Fabrication -> Partially embedded NPs -> No analytical (approximated) method physically introduces the incrustation degree. There are numerical solutions and Effective Medium Theories approaching the problem but the later only as a fitting method.
- Objectives: What question are you answering with your work.
Can optical non invasive tests (IR-Vis) retrieve the average incrustation degree for monolayers of small spherical particles?
- Methology: What are your secondary goals so you achieve your objective. Also, how are you answering yout question: which method or model.
Bruggeman homogenization theories on bidimensional systems?
Is the dipolar approximation is enough or do we need more multipolar terms?
Do we need the depolarization factors?
- Structure: How is this thesis divides and what is the content of each chapter.

Chapter 1

Optical Properties of Single Plasmonic Nanoparticles

The problem studied in this thesis corresponds to the theoretical analysis of the Localized Surface Plasmon Resonances (LSPR) excited on plasmonic spherical nanoparticles (NPs) when these are under realistic experimental conditions, such as those present on plasmonic biosensors, where the NPs are partially embedded into a substrate [1]. The theoretical analysis consists on the numerical calculation of the absorption, scattering and extinction cross sections of a partially embedded metal NP employing the Finite Element Method (FEM), nevertheless, to verify the validity of the obtained results, the problem of the absorption and scattering of light by an isolated particle must be addressed. In this chapter, we revisit the general solution of the light absorption and scattering by both an arbitrary particle and by a spherical particle, given by the Mie Theory [2].

1.1 The Optical Theorem: Amplitude Matrix and Cross Sections

Let $\mathbf{E}^i = \mathbf{E}_0^i \exp(i\mathbf{k}^i \cdot \mathbf{r})$ be the electric field of an incident monochromatic plane wave with constant amplitude \mathbf{E}_0^i traveling through a non-dispersive medium with refractive index n_m , denominated matrix, in the direction $\mathbf{k}^i = k\hat{\mathbf{k}}^i$, with $k = (\omega/c)n_m$ the wave number of the plane wave into the matrix, and let \mathbf{E}^{sca} be the scattered electric field due to a particle with arbitrary shape embedded into the matrix. In general, the scattered electric field propagates in all directions but for a given point $\mathbf{r} = r\hat{\mathbf{e}}_r$ the traveling direction is defined by the vector $\mathbf{k}^{sca} = k\hat{\mathbf{k}}^{sca} = k\hat{\mathbf{e}}_r$. Due to the linearity of the Maxwell's equations, the incident and scattered electric fields in the far field regime are related by the linear relation [3],

$$\mathbf{E}^{sca} = \frac{\exp(i\mathbf{k}^{sca} \cdot \mathbf{r})}{r} \mathbb{F}(\hat{\mathbf{k}}^{sca}, \hat{\mathbf{k}}^i) \mathbf{E}^i, \quad (1.1)$$

where $\mathbb{F}(\hat{\mathbf{k}}^{sca}, \hat{\mathbf{k}}^i)$ is the scattering amplitude matrix from direction $\hat{\mathbf{k}}^i$ into $\hat{\mathbf{k}}^{sca}$. Since only the far field is considered, both the incident and the scattered electric field can be decomposed into two linearly independent components perpendicular to \mathbf{k}^i and \mathbf{k}^{sca} , respectively, each forming a

right-hand orthonormal system. If the particle acting as a scatterer has a symmetric shape, it is convenient to define the orthonormal systems relative to the scattering plane, which is the plane containing \mathbf{k}^i and \mathbf{k}^{sca} , since the elements of $\mathbb{F}(\hat{\mathbf{k}}^{sca}, \hat{\mathbf{k}}^i)$ simplify when represented in these bases [3]. By defining the directions perpendicular (\perp) and parallel (\parallel) to the scattering plane, the incident and scattered electric fields can be written as

$$\mathbf{E}^i = (E_{\parallel}^i \hat{\mathbf{e}}_{\parallel}^i + E_{\perp}^i \hat{\mathbf{e}}_{\perp}^i) \exp(i\mathbf{k}^i \cdot \mathbf{r}), \quad (1.2)$$

$$\mathbf{E}^{sca} = (E_{\parallel}^{sca} \hat{\mathbf{e}}_{\parallel}^{sca} + E_{\perp}^{sca} \hat{\mathbf{e}}_{\perp}^{sca}) \frac{\exp(i\mathbf{k}^{sca} \cdot \mathbf{r})}{r}, \quad (1.3)$$

where an harmonic time dependence $\exp(-i\omega t)$ has been suppressed, and where it has been assumed that the scattered field is described by a spherical wave; the superindex ‘i’ (‘sca’) denotes the orthonormal system defined by the incident plane wave (scattered fields). Since $\{\hat{\mathbf{e}}_{\perp}^i, \hat{\mathbf{e}}_{\parallel}^i, \hat{\mathbf{k}}^i\}$ and $\{\hat{\mathbf{e}}_{\perp}^{sca}, \hat{\mathbf{e}}_{\parallel}^{sca}, \hat{\mathbf{k}}^{sca}\}$ are right-hand orthonormal systems, they are related as follows

$$\hat{\mathbf{e}}_{\perp}^i = \hat{\mathbf{e}}_{\perp}^{sca} = \hat{\mathbf{k}}^{sca} \times \hat{\mathbf{k}}^i, \quad \hat{\mathbf{e}}_{\parallel}^i = \hat{\mathbf{k}}^i \times \hat{\mathbf{e}}_{\perp}^i, \quad \text{and} \quad \hat{\mathbf{e}}_{\parallel}^{sca} = \hat{\mathbf{k}}^{sca} \times \hat{\mathbf{e}}_{\perp}^{sca}. \quad (1.4)$$

As the Eqs. (1.4) suggest, the unit vector bases of the orthonormal systems relative to the scattering plane depend on the scattering direction. For example, if the incident plane wave travels along the z axis, then $\hat{\mathbf{k}}^i = \hat{\mathbf{e}}_z$ and $\hat{\mathbf{k}}^{sca} = \hat{\mathbf{e}}_r$. Thus, according to Eqs. (1.4), the unit vector bases of the systems relative to the scattering plane are $\hat{\mathbf{e}}_{\parallel}^i = \cos \varphi \hat{\mathbf{e}}_x + \sin \varphi \hat{\mathbf{e}}_y$, $\hat{\mathbf{e}}_{\parallel}^{sca} = \hat{\mathbf{e}}_\theta$ and $\hat{\mathbf{e}}_{\perp}^i = \hat{\mathbf{e}}_{\perp}^{sca} = -\hat{\mathbf{e}}_\varphi$, with θ the polar angle and φ azimuthal angle. In Fig. 1.1 the unit vector systems (purple) based on the scattering plane (green) defined by the vectors $\hat{\mathbf{k}}^i = \hat{\mathbf{e}}_z$ and $\hat{\mathbf{k}}^{sca} = \hat{\mathbf{e}}_r$ are shown, along with the Cartesian (blue) and spherical (black) unit vector bases.

After an incident plane wave interacts with a particle with a possible complex refractive index $n_p(\omega)$, the total electric field outside the particle is given by the sum of the incident and the scattered fields. Therefore, the time averaged Poynting vector $\langle \mathbf{S} \rangle_t$, denoting the power flow per unit area, of the total field is given by

$$\langle \mathbf{S} \rangle_t = \underbrace{\frac{1}{2} \operatorname{Re} (\mathbf{E}^i \times \mathbf{H}^{i*})}_{\langle \mathbf{S}^i \rangle_t} + \underbrace{\frac{1}{2} \operatorname{Re} (\mathbf{E}^{sca} \times \mathbf{H}^{sca*})}_{\langle \mathbf{S}^{sca} \rangle_t} + \underbrace{\frac{1}{2} \operatorname{Re} (\mathbf{E}^i \times \mathbf{H}^{sca*} + \mathbf{E}^{sca} \times \mathbf{H}^{i*})}_{\langle \mathbf{S}^{ext} \rangle_t}, \quad (1.5)$$

where $(*)$ is the complex conjugate operation and where the total Poynting vector is separated into the contribution from the incident field $\langle \mathbf{S}^i \rangle_t$, from the scattered field $\langle \mathbf{S}^{sca} \rangle_t$ and from their cross product denoted by $\langle \mathbf{S}^{ext} \rangle_t$. By means of the Faraday-Lenz Law and Eq. (1.1), the contribution to the Poynting vector from the incident and the scattered fields can be rewritten as

$$\langle \mathbf{S}^i \rangle_t = \frac{\|\mathbf{E}_0^i\|^2}{2Z_m} \hat{\mathbf{k}}^i, \quad \text{and} \quad \langle \mathbf{S}^{sca} \rangle_t = \frac{\|\mathbf{E}^{sca}\|^2}{2Z_m} \hat{\mathbf{k}}^{sca} = \frac{\|\mathbb{F}(\hat{\mathbf{k}}^{sca}, \hat{\mathbf{k}}^i) \mathbf{E}^i\|^2}{2Z_m r^2} \hat{\mathbf{k}}^{sca}, \quad (1.6)$$

with $Z_m = \sqrt{\mu_m/\epsilon_m}$, the impedance of the non-dispersive matrix, while the crossed contribution

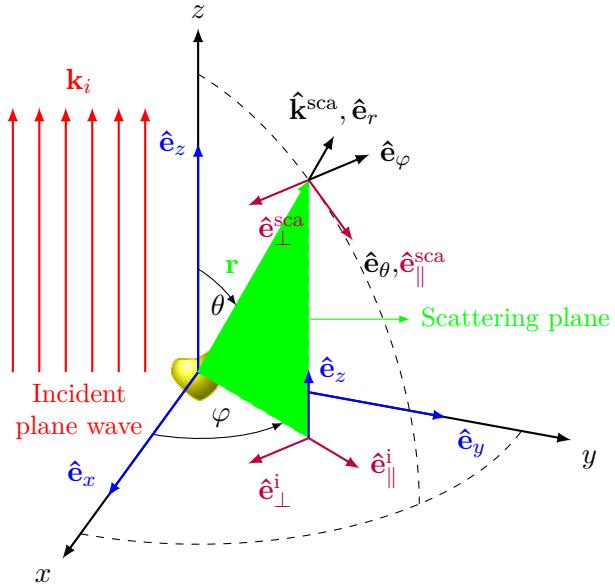


Fig. 1.1: The scattering plane (green) is defined by the vectors $\hat{\mathbf{k}}^i$, direction of the incident plane wave (red), and $\hat{\mathbf{k}}^{sca}$, direction of the scattered field in a given point \vec{r} . If the direction of the incident plane wave is chosen to be $\hat{\mathbf{e}}_z$, the parallel and perpendicular components of the incident field relative to the scattering plane are $\hat{\mathbf{e}}_||^i = \cos \varphi \hat{\mathbf{e}}_x + \sin \varphi \hat{\mathbf{e}}_y$ and $\hat{\mathbf{e}}_\perp^i = -\hat{\mathbf{e}}_\varphi$, while the components of the scattering field relative to the scattering plane are $\hat{\mathbf{e}}_\parallel^{sca} = \hat{\mathbf{e}}_\theta$, $\hat{\mathbf{e}}_\perp^{sca} = -\hat{\mathbf{e}}_\varphi$. The cartesian unit vector basis is shown in blue, the spherical unit vector basis in black, while the basis of the orthonormal systems relative to the scattering plane are shown in purple.

is given by

$$\langle \mathbf{S}^{ext} \rangle_t = \text{Re} \left\{ \frac{\exp[-i(\mathbf{k}^{sca} - \mathbf{k}^i) \cdot \mathbf{r}]}{2Z_m r^2} [\hat{\mathbf{k}}^{sca} (\mathbf{E}_0^i \cdot \mathbb{F}^* \mathbf{E}^{i*}) - \mathbb{F}^* \mathbf{E}^{i*} (\mathbf{E}_0^i \cdot \hat{\mathbf{k}}^{sca})] + \frac{\exp[i(\mathbf{k}^{sca} - \mathbf{k}^i) \cdot \mathbf{r}]}{2Z_m r^2} [\hat{\mathbf{k}}^i (\mathbb{F} \mathbf{E}^i \cdot \mathbf{E}_0^{i*}) - \mathbf{E}_0^{i*} (\mathbb{F} \mathbf{E}^i \cdot \hat{\mathbf{k}}^i)] \right\}, \quad (1.7)$$

where the scattering amplitude matrix is evaluated as $\mathbb{F}(\hat{\mathbf{k}}^{sca}, \hat{\mathbf{k}}^i)$.

The power scattered by the particle can be calculated by integrating $\langle \mathbf{S}^{sca} \rangle_t$ in a closed surface surrounding the particle; if the scattered power is normalized by the irradiance of the incident field $\|\langle \mathbf{S}^i \rangle_t\|$, it is obtained a quantity with units of area known as the scattering cross section C_{sca} , given by

Scattering Cross Section

$$C_{sca} = \frac{2Z_m}{\|\mathbf{E}_0\|^2} \oint \langle \mathbf{S}^{sca} \rangle \cdot d\mathbf{a} = \oint \frac{\|\mathbb{F}(\hat{\mathbf{k}}^{sca}, \hat{\mathbf{k}}^i) \mathbf{E}^i\|^2}{\|\mathbf{E}_0^i\|^2} d\Omega, \quad (1.8)$$

where $d\Omega$ is the solid angle differential. In a similar manner, an absorption cross section C_{abs} can be defined as well. On the one side, the absorption cross section is given by the integral on

a closed surface of $-\langle \mathbf{S} \rangle_t$ [Eq. (1.5)] divided by the irradiance of the incident field, where the minus sign is chosen so that $C_{\text{abs}} > 0$ if the particle absorbs energy [2]. On the other side, if an Ohmic material for the particle with conductivity $\sigma(\omega) = i\omega n_p^2(\omega)$ [4] is assumed, through Joule's Heating Law [3] the absorption cross section can be computed as

Ohmic Particle - Absorption Cross Section

$$C_{\text{abs}} = \frac{1}{2} \int \frac{\text{Re}(\mathbf{j} \cdot \mathbf{E}^{\text{int}*})}{\|\mathbf{E}_0^i\|^2 / 2Z_m} dV = \int \omega Z_m \text{Im}(n_p^2) \frac{\|\mathbf{E}^{\text{int}}\|^2}{\|\mathbf{E}_0^i\|^2} dV, \quad (1.9)$$

where integration is performed inside the particle, and \mathbf{j} and \mathbf{E}^{int} , are the volumetric electric current density and the total electric field in this region, respectively. Both the scattering and the absorption cross sections are quantities related to the optical signature of a particle [5], and their relation can be made explicit by performing the surface integral representation of C_{abs} and defining C_{ext} , that is,

$$\begin{aligned} C_{\text{abs}} &= -\frac{2Z_m}{\|\mathbf{E}_0^i\|^2} \int (\langle \mathbf{S}^i \rangle_t + \langle \mathbf{S}^{\text{sca}} \rangle_t + \langle \mathbf{S}^{\text{ext}} \rangle_t) \cdot d\mathbf{a} \\ &= -C_{\text{sca}} - \frac{2Z_m}{\|\mathbf{E}_0^i\|^2} \int \langle \mathbf{S}^{\text{ext}} \rangle_t \cdot \hat{\mathbf{e}}_r d\Omega \\ &= -C_{\text{sca}} + C_{\text{ext}}, \end{aligned} \quad (1.10)$$

where the contribution of $\langle \mathbf{S}^i \rangle_t$ to the integral is zero since a non-dispersive matrix was assumed. From Eq.(1.10) it can be seen that C_{ext} takes into account both mechanisms for energy loses (scattering and absorption), thus it is called the extinction cross section. To solve the integral in Eq. (1.10) let us define θ as the angle between $\hat{\mathbf{k}}^{\text{sca}}$ and $\hat{\mathbf{k}}^i$ as the polar angle and φ as the azimuthal angle as shown in Fig 1.1. With this election of coordinates, the extinction cross section can be computed as

$$\begin{aligned} C_{\text{ext}} &= -\text{Re} \left\{ \frac{\exp(-ikr)}{\|\mathbf{E}_0^i\|^2} \oint \exp(ikr \cos \theta) (1) (\mathbf{E}^i \cdot \mathbb{F}^* \mathbf{E}^{i*}) d\Omega \right. \\ &\quad + \frac{\exp(ikr)}{\|\mathbf{E}_0^i\|^2} \oint \exp(-ikr \cos \theta) \cos \theta (\mathbf{E}^{i*} \cdot \mathbb{F} \mathbf{E}^i) d\Omega \\ &\quad \left. + \frac{\exp(ikr)}{\|\mathbf{E}_0^i\|^2} \oint \exp(-ikr \cos \theta) \sin \theta (E_{0,x}^i \cos \varphi + E_{0,y}^i \sin \varphi) (\mathbb{F} \mathbf{E}^i \cdot \mathbf{k}^i) d\Omega \right\} \end{aligned} \quad (1.11)$$

where the relations $\hat{\mathbf{k}}^{\text{sca}} \cdot \hat{\mathbf{e}}_r = 1$, $\hat{\mathbf{k}}^i \cdot \hat{\mathbf{e}}_r = \cos \theta$ and $\mathbf{E}^{\text{sca}} \cdot \hat{\mathbf{e}}_r = 0$ were employed. The integrals in Eq. (1.11) can be solved by a two-fold integration by parts on the polar angle θ and by depreciating the terms proportional to r^{-2} . This process leads to a zero contribution from the integrand proportional to $\sin \theta$ of Eq. (1.11), and after arranging the other terms in their real and imaginary parts, it follows that C_{ext} depends only in the forward direction $\hat{\mathbf{k}}^{\text{sac}} = \hat{\mathbf{k}}^i$ ($\theta = 0$). This result is known as the Optical Theorem whose mathematical expression is given by [3, 5, 6]

Optical Theorem - Extinction Cross Section

$$C_{\text{ext}} = C_{\text{abs}} + C_{\text{sca}} = \frac{4\pi}{k\|\mathbf{E}_0^i\|^2} \text{Im} \left[\mathbf{E}_0^i \cdot \mathbb{F}^*(\hat{\mathbf{k}}^i, \hat{\mathbf{k}}^i) \mathbf{E}_0^{i*} \right]. \quad (1.12)$$

From Eqs. (1.5) and (1.12) it can be seen that the extinction of light, the combined result of scattering and absorption as energy loss mechanisms, is also a manifestation of the interference between the incident and the scattered fields and that the overall effect of the light extinction can be fully understood by analyzing the amplitude of the scattering field in the forward direction. It is worth noting that Eq. (1.12) is an exact relation but its usefulness is bond to the correct evaluation of the scattering amplitude matrix \mathbb{F} [3]. Thus, in the following sections a scattering problem with spherical symmetry will be assumed, so that the exact solution to the scattering amplitude matrix can be developed; this solution is known as Mie Theory.

1.2 Mie Scattering

In the previous section, it was concluded that the extinction of light due to the interaction between a particle and a monochromatic plane wave can be determinated through the amplitude of the scattered field in the forward direction. This is stated in the Optical Theorem, which is an exact relation, but inaccuracies can arise when either the scattering amplitude matrix or extinction cross section is approximated¹. A particular case in which the scattering amplitude matrix can be exactly calculated is when the scatterer has spherical symmetry. In order to address this special case it will be introduced a vectorial basis with spherical symmetry, known as the Vector Spherical Harmonics (VSH). Once the SVH are defined, they will be used to write a monochromatic plane wave and, lastly, the scattered field by a spherical particle will be calculated by imposing the continuity of the tangential components of the electric and magnetic field.

1.2.1 Vector Spherical Harmonics

The electric and magnetic field, denoted as \mathbf{E} and \mathbf{B} , respectively, are a solution to the homogeneous vectorial Helmholtz when an harmonic time dependence and a spacial domain with no external charge nor current densities is assumed, that is,

Vectorial Helmholtz Equation

$$\nabla^2 \mathbf{E}(\mathbf{r}, \omega) + k^2 \mathbf{E}(\mathbf{r}, \omega) = \mathbf{0}, \quad (1.13a)$$

$$\nabla^2 \mathbf{B}(\mathbf{r}, \omega) + k^2 \mathbf{B}(\mathbf{r}, \omega) = \mathbf{0}. \quad (1.13b)$$

where the vectorial operator ∇^2 must be understood as $\nabla^2 = \nabla(\nabla \cdot) - \nabla \times \nabla \times$, and k is the

¹See for example Section 2.4 from Ref. [3] on the Rayleigh Scattering and Section 21.7 from Ref. [7] on Thompson scattering.

1. OPTICAL PROPERTIES OF SINGLE PLASMONIC NANOPARTICLES

wave number in the matrix, which must follow the relation of dispersion $k = (\omega/c)n_m$, with $n_m = \sqrt{\mu_m \epsilon_m / \mu_0 \epsilon_0}$ the refractive index of the matrix, μ_m its magnetic permeability and ϵ_m its dielectric function. It is possible to build a basis set for the electric and magnetic fields as long as the elements of this basis are also solution to Eq. (1.13). One alternative is to employ the following set of vector functions

$$\mathbf{L} = \nabla \psi, \quad (1.14a)$$

$$\mathbf{M} = \nabla \times (\mathbf{r}\psi), \quad (1.14b)$$

$$\mathbf{N} = \frac{1}{k} \nabla \times \mathbf{M}, \quad (1.14c)$$

that are solution to the homogeneous vectorial Helmholtz equation as long as the scalar function ψ is solution to the scalar Helmholtz equation²

$$\nabla^2 \psi + k^2 \psi = 0. \quad (1.15)$$

The triad $\{\mathbf{L}, \mathbf{M}, \mathbf{N}\}$ is a set of vectors³ that obey Helmholtz equation *i.e.*, they can be directly identify as electric or magnetic fields. The elements of the vector basis from Eq. (1.14) are known as the Vectorial Spherical Harmonics (VSH) as defined by Stratton [8], and Bohren and Huffman [2] and the scalar function ψ is known as the generating function of the VSH. From the definition of the VSH in Eqs. (1.14) it can be seen that \mathbf{L} has only a longitudinal component while \mathbf{M} and \mathbf{N} have only transversal components; specifically \mathbf{M} is tangential to any sphere of radius $\|\mathbf{r}\|$.

If spherical coordinates are chosen, and it is assumed that $\psi(r, \theta, \varphi) = R(r)\Theta(\theta)\Phi(\varphi)$, then Eq. (1.15) can be decouple into three ordinary differential equations:

$$\frac{d^2\Phi}{d\varphi^2} + m^2\Phi = 0, \quad (1.16)$$

$$\frac{1}{\sin \theta} \frac{d}{d\theta} \left(\sin \theta \frac{d\Theta}{d\theta} \right) + \left[\ell(\ell+1) - \frac{m^2}{\sin^2 \theta} \right] \Theta = 0, \quad (1.17)$$

$$\frac{d}{dr} \left(r^2 \frac{dR}{dr} \right) + \left[(kr)^2 - \ell(\ell+1) \right] R = 0, \quad (1.18)$$

where ℓ can take natural values and zero, and $|m| \leq \ell$ so Φ and Θ are univalued and finite on a sphere. Eqs. (1.17) and (1.18) can be rewritten as

$$(1 - \mu^2) \frac{d^2\Theta}{d\mu^2} - 2\mu \frac{d\Theta}{d\mu} + \left[\ell(\ell+1) - \frac{m^2}{1 - \mu^2} \right] \Theta = 0, \quad \text{with } \mu = \cos \theta, \quad (1.19)$$

$$\rho \frac{d}{d\rho} \left(\rho \frac{dZ}{d\rho} \right) + \left[\rho^2 - \left(\ell + \frac{1}{2} \right)^2 \right] Z = 0, \quad \text{with } Z = R\sqrt{\rho} \text{ and } \rho = kr. \quad (1.20)$$

²This result can be proven by considering the following: Let f be \mathcal{C}^3 and \mathbf{F} a \mathcal{C}^2 . Then, it is true that $\nabla^2(\nabla f) = \nabla(\nabla^2 f)$, and $\nabla \times (\nabla^2 \mathbf{F}) = \nabla^2(\nabla \times \mathbf{F})$.

³Employing the Einstein sum convention with ϵ_{ijk} the Levi-Civita symbol, Eq. (1.14b) can be written as follows: $M_i = [\nabla \times (\mathbf{r}\psi)]_i = \epsilon_{ijk} \partial_j (r_k \psi) = \psi \epsilon_{ijk} \partial_j (r_k) - \epsilon_{ikj} r_k \partial_j \psi = \psi [\nabla \times \mathbf{r}]_i - [\mathbf{r} \times \nabla \psi]_i = -[\mathbf{r} \times \nabla \psi]_i = [\mathbf{L} \times \mathbf{r}]_i$, therefore \mathbf{M} is orthogonal to \mathbf{L} and \mathbf{r} . From Eq. (1.14c) $\mathbf{M} \cdot \mathbf{N} = 0$, so \mathbf{M} is orthogonal to \mathbf{N} . As it will be shown, not necessarily \mathbf{L} is orthogonal to \mathbf{N} in a geometrical sense.

The solution to Eq. (1.19) are the associated Legendre functions $P_\ell^m(\mu)$ and to Eq. (1.20) the solution is given by the spherical Bessel functions of the first (j_ℓ) and second (y_ℓ) kind, and the spherical Hankel functions of first ($h_\ell^{(1)} = j_\ell + iy_\ell$) and second ($h_\ell^{(2)} = j_\ell - iy_\ell$) kind. Following the convention from most literature on Mie Scattering [7], the solution to Eq. (1.16) will be decompose into an odd (o) and an even (e) solution, that is, as sine and cosine functions, thus restricting the values of m to non-negative integers. After this procedure, it is determined that the generating function of the VSH is given by

ψ : Generating function of the vectorial spherical harmonics

$$\psi_{e\ell m}(r, \theta, \varphi) = \cos(m\varphi)P_\ell^m(\cos\theta)z_\ell(kr), \quad (1.21a)$$

$$\psi_{o\ell m}(r, \theta, \varphi) = \sin(m\varphi)P_\ell^m(\cos\theta)z_\ell(kr). \quad (1.21b)$$

where z_ℓ stands for any of the four solutions to the radial equation [Eq. (1.20)]. Substituting Eq. (1.21a) in Eqs. (1.14a)–(1.14c) one finds the even VSH

Even vectorial spherical harmonics

$$\begin{aligned} \mathbf{L}_{em\ell} = & k \cos(m\varphi) P_\ell^m(\cos\theta) \frac{d}{dz_\ell(kr)}(kr) \hat{\mathbf{e}}_r + k \cos(m\varphi) \frac{z_\ell(kr)}{kr} \frac{dP_\ell^m(\cos\theta)}{d\theta} \hat{\mathbf{e}}_\theta \\ & - km \sin(m\varphi) \frac{P_\ell^m(\cos\theta)}{\sin\theta} \frac{z_\ell(kr)}{kr} \hat{\mathbf{e}}_\varphi \end{aligned} \quad (1.22a)$$

$$\mathbf{M}_{em\ell} = -m \sin(m\varphi) z_\ell(kr) \frac{P_\ell^m(\cos\theta)}{\sin\theta} \hat{\mathbf{e}}_\theta - \cos(m\theta) z_\ell(kr) \frac{dP_\ell^m(\cos\theta)}{d\theta} \hat{\mathbf{e}}_\varphi, \quad (1.22b)$$

$$\begin{aligned} \mathbf{N}_{em\ell} = & \cos(m\varphi) \frac{z_\ell(kr)}{kr} \ell(\ell+1) P_\ell^m(\cos\theta) \hat{\mathbf{e}}_r + \cos(m\varphi) \frac{1}{kr} \frac{d[kr z_\ell(kr)]}{d(kr)} \frac{dP_\ell^m(\cos\theta)}{d\theta} \hat{\mathbf{e}}_\theta \\ & - m \sin(m\varphi) \frac{1}{kr} \frac{d[kr z_\ell(kr)]}{d(kr)} \frac{P_\ell^m(\cos\theta)}{\sin\theta} \hat{\mathbf{e}}_\varphi, \end{aligned} \quad (1.22c)$$

where the term $\ell(\ell+1)P_\ell^m$ arises since the associated Legendre functions obeys Eq. (1.19). Likewise, the odd VSH are given by

Odd vectorial spherical harmonics

$$\begin{aligned} \mathbf{L}_{om\ell} = & k \sin(m\varphi) P_\ell^m(\cos\theta) \frac{d}{dz_\ell(kr)}(kr) \hat{\mathbf{e}}_r + k \sin(m\varphi) \frac{z_\ell(kr)}{kr} \frac{dP_\ell^m(\cos\theta)}{d\theta} \hat{\mathbf{e}}_\theta \\ & + km \cos(m\varphi) \frac{P_\ell^m(\cos\theta)}{\sin\theta} \frac{z_\ell(kr)}{kr} \hat{\mathbf{e}}_\varphi \end{aligned} \quad (1.23a)$$

$$\mathbf{M}_{om\ell} = m \cos(m\varphi) z_\ell(kr) \frac{P_\ell^m(\cos\theta)}{\sin\theta} \hat{\mathbf{e}}_\theta - \sin(m\theta) z_\ell(kr) \frac{dP_\ell^m(\cos\theta)}{d\theta} \hat{\mathbf{e}}_\varphi, \quad (1.23b)$$

$$\begin{aligned} \mathbf{N}_{om\ell} = & \sin(m\varphi) \frac{z_\ell(kr)}{kr} \ell(\ell+1) P_\ell^m(\cos\theta) \hat{\mathbf{e}}_r + \sin(m\varphi) \frac{1}{kr} \frac{d[kr z_\ell(kr)]}{d(kr)} \frac{dP_\ell^m(\cos\theta)}{d\theta} \hat{\mathbf{e}}_\theta \\ & + m \cos(m\varphi) \frac{1}{kr} \frac{d[kr z_\ell(kr)]}{d(kr)} \frac{P_\ell^m(\cos\theta)}{\sin\theta} \hat{\mathbf{e}}_\varphi. \end{aligned} \quad (1.23c)$$

The election on z_ℓ in Eqs. (1.22) and (1.23) is due to the physical constrains of the scattering problem. The spherical Bessel function of first kind, unlike the other three proposed solution to the radial equation, is finite at $r = 0$, thus it is appropriate for the internal electric field and plane waves. This election of z_ℓ will be denoted in the VSH with the superscript (1). On the other hand, the asymptotic behavior ($\ell \ll \rho$) of the Hankel function of first kind $h^{(1)} = j_\ell + iy_\ell$ and its derivative are outgoing spherical waves [2]

$$h_\ell^{(1)}(\rho) \approx (-i)^\ell \frac{\exp(i\rho)}{i\rho} \quad \text{and} \quad \frac{dh_\ell^{(1)}(\rho)}{d\rho} \approx (-i)^\ell \frac{\exp(i\rho)}{\rho} \quad (1.24)$$

which are suited for the scattered field; the VSH with $z_\ell = h_\ell^{(1)}$ will be then, denoted with the superscript (3).

Within this text, the VSH were define in Eq. (1.14) under the condition of being a solution to the vectorial Helmholtz equation, which lead to the generating function ψ to be a solution to the scalar Helmholtz equation, nevertheless there are other definitions as discussed by Barrera, Estevez, and Giraldo [9]. The chosen definition of the VSH allows the VSH to be interpreted directly as electric and magnetic fields, specifically identifying \mathbf{N} with the electric contribution and \mathbf{M} with the magnetic, as it will be shown in the following sections.

1.2.2 Incident, Scattered and Internal Electric Field

Let \mathbf{E}^i be a x polarized plane wave traveling in the vertical direction \mathbf{e}_z ; its representation in the canonical spherical basis is

$$\mathbf{E}^i(\mathbf{r}) = E_0 (\sin \theta \cos \varphi \hat{\mathbf{e}}_r + \cos \theta \cos \varphi \hat{\mathbf{e}}_\theta - \sin \varphi \hat{\mathbf{e}}_\varphi) \exp(ikr \cos \theta). \quad (1.25)$$

The monochromatic plane wave is a transversal wave, thus it can be written in terms of only the VSH $\mathbf{M}^{(1)}$ and $\mathbf{N}^{(1)}$, where the radial dependency is given by j_ℓ since the monochromatic plane wave is finite everywhere. Even more, due to the dependency on φ , it is only restricted to values of $m = 1$. By inspection on the radial component of \mathbf{E}^i , proportional to $\cos \varphi$ it depends only on $\mathbf{N}_{e1\ell}^{(1)}$, and on the azimuthal component, proportional to $\sin \varphi$, it can depend only on $\mathbf{M}_{o1\ell}^{(1)}$. Thus, Eq. (1.25) can be written as the linear combination of $\mathbf{N}_{e1\ell}^{(1)}$ and $\mathbf{M}_{o1\ell}^{(1)}$. Through the orthogonality relations of the VSH, the x polarized plane wave can be written as [8]

$$\mathbf{E}^i(\mathbf{r}) = E_0 \sum_\ell \frac{i^\ell (2\ell + 1)}{\ell(\ell + 1)} (\mathbf{M}_{o1\ell}^{(1)} - i\mathbf{N}_{e1\ell}^{(1)}), \quad (1.26a)$$

$$\mathbf{H}^i(\mathbf{r}) = \frac{-kE_0}{\mu\omega} \sum_\ell \frac{i^\ell (2\ell + 1)}{\ell(\ell + 1)} (\mathbf{M}_{e1\ell}^{(1)} + i\mathbf{N}_{o1\ell}^{(1)}). \quad (1.26b)$$

In the problem of scattering due to a spherical particle of radius a , the continuity conditions on the parallel components on the electric and magnetic fields are written as

$$(\mathbf{E}^i + \mathbf{E}^{\text{sca}} - \mathbf{E}^{\text{int}}) \Big|_{r=a} \times \hat{\mathbf{e}}_r = (\mathbf{H}^i + \mathbf{H}^{\text{sca}} - \mathbf{H}^{\text{int}}) \Big|_{r=a} \times \hat{\mathbf{e}}_r = 0, \quad (1.27)$$

with \mathbf{E}^{sca} (\mathbf{E}^{int}) the scattered (internal) electric field and \mathbf{H}^{sca} (\mathbf{H}^{int}) the scattered (internal) magnetic field. If the incident field \mathbf{E}^i is given by a x polarized plane wave [Eq. (1.25)] then the scattered and internal fields can be written also as a linear combination of $\mathbf{M}_{o1\ell}$ and $\mathbf{N}_{e1\ell}$. The internal field is finite inside the particle, thus the radial dependency is given by the function $j_\ell(k_p a)$ with k_p the wave number inside the particle, while it is chosen the spherical Hankel function of first kind $h^{(1)}(ka)$ for the scattered fields due to its asymptotic behavior of a spherical outgoing wave, such election for the radial dependency is denoted by the superscript (3) over the VSH. To simplify the following steps, the scattered and the internal electric files are proposed as

$$\mathbf{E}^{\text{sca}}(\mathbf{r}) = E_0 \sum_{\ell} \frac{i^\ell(2\ell+1)}{\ell(\ell+1)} (ia_\ell \mathbf{N}_{e1\ell}^{(3)} - b_\ell \mathbf{M}_{o1\ell}^{(3)}), \quad (1.28a)$$

$$\mathbf{E}^{\text{int}}(\mathbf{r}) = E_0 \sum_{\ell} \frac{i^\ell(2\ell+1)}{\ell(\ell+1)} (c_\ell \mathbf{M}_{o1\ell}^{(1)} - id_\ell \mathbf{N}_{e1\ell}^{(1)}), \quad (1.28b)$$

with the respective magnetic fields

$$\mathbf{H}^{\text{sca}}(\mathbf{r}) = \frac{-kE_0}{\mu\omega} \sum_{\ell} \frac{i^\ell(2\ell+1)}{\ell(\ell+1)} (ib_\ell \mathbf{N}_{o1\ell}^{(3)} + a_\ell \mathbf{M}_{e1\ell}^{(3)}), \quad (1.29a)$$

$$\mathbf{H}^{\text{int}}(\mathbf{r}) = \frac{-kE_0}{\mu_p\omega} \sum_{\ell} \frac{i^\ell(2\ell+1)}{\ell(\ell+1)} (d_\ell \mathbf{M}_{e1\ell}^{(1)} + ic_\ell \mathbf{N}_{o1\ell}^{(1)}). \quad (1.29b)$$

Since only the term $m = 1$ is taken into account, it is convenient to define the angular functions

$$\pi_\ell(\cos\theta) = \frac{P_\ell^1(\cos\theta)}{\sin\theta}, \quad \text{and} \quad \tau_\ell(\cos\theta) = \frac{dP_\ell^1(\cos\theta)}{d\theta}, \quad (1.30)$$

which are not orthogonal but their addition and subtraction are, that is $\pi_\ell \pm \tau_\ell$ are orthogonal functions [2]. After substitution of Eqs. (1.26), (1.28) and (1.29) into Eq. (1.27) and considering the orthogonality of the odd and even VSH, of the vectors \mathbf{M} and \mathbf{N} , and of $\pi_\ell \pm \tau_\ell$, it is shown that the coefficients a_ℓ , b_ℓ , c_ℓ and d_ℓ are given by two decoupled equation systems

$$\begin{pmatrix} [xh_\ell^{(1)}(x)] & (\mu/\mu_p)[(mx)j_\ell(mx)] \\ m[xh_\ell^{(1)}(x)]' & [(mx)j_\ell(mx)]' \end{pmatrix} \begin{pmatrix} a_\ell \\ d_\ell \end{pmatrix} = \begin{pmatrix} [xj_\ell(x)] \\ m[xj_\ell(x)]' \end{pmatrix}, \quad (1.31)$$

and

$$\begin{pmatrix} m[xh_\ell^{(1)}(x)] & [(mx)j_\ell(mx)] \\ [xh_\ell^{(1)}(x)]' & (\mu/\mu_p)[(mx)j_\ell(mx)]' \end{pmatrix} \begin{pmatrix} b_\ell \\ c_\ell \end{pmatrix} = \begin{pmatrix} m[xj_\ell(x)] \\ [xj_\ell(x)]' \end{pmatrix}, \quad (1.32)$$

where $m = k_p/k = n_p/n_m$ is the contrast between the sphere and the matrix, $x = ka = 2\pi n_m(a/\lambda)$ is the size parameter and ('') denotes the derivative respect to the argument of the spherical Bessel or Hankel functions. The Eqs. (1.31) and (1.32) are simplified when the Riccati-Bessel functions $\psi_\ell(\rho) = \rho j_\ell(\rho)$ and $\xi(\rho) = \rho h_\ell^{(1)}(\rho)$ are introduced.

When a no magnetic particle nor matrix are assumed ($\mu_p = \mu = \mu_0$), the coefficients a_ℓ and b_ℓ are known as the Mie Coefficients whose expression is calculated by inverting Eqs. (1.31) and (1.32), leading to

Mie Coefficients

$$a_\ell = \frac{\psi_\ell(x)\psi'_\ell(mx) - m\psi_\ell(mx)\psi'_\ell(x)}{\xi_\ell(x)\psi'_\ell(mx) - m\psi_\ell(mx)\xi'_\ell(x)}, \quad (1.33a)$$

$$b_\ell = \frac{m\psi_\ell(x)\psi'_\ell(mx) - \psi_\ell(mx)\psi'_\ell(x)}{m\xi_\ell(x)\psi'_\ell(mx) - \psi_\ell(mx)\xi'_\ell(x)}. \quad (1.33b)$$

Likewise, the coefficients c_ℓ and d_ℓ are

$$c_\ell = \frac{-m\xi'_\ell(x)\psi_\ell(x) + m\xi_\ell(x)\psi'_\ell(x)}{m\xi_\ell(x)\psi'_\ell(mx) - \psi_\ell(mx)\xi'_\ell(x)}, \quad (1.34a)$$

$$d_\ell = \frac{-m\xi'_\ell(x)\psi_\ell(x) + m\psi'_\ell(mx)\psi'_\ell(x)}{\xi_\ell(x)\psi'_\ell(mx) - m\psi_\ell(mx)\xi'_\ell(x)}. \quad (1.34b)$$

Even though the coefficients of the linear combination for the scattered and internal fields were obtained by assuming an x polarized incident field, due to the spherical symmetry of the problem, by applying the transformation $\varphi \rightarrow \varphi + \pi/2$ the same procedure is valid for a y polarized incident field [2], therefore all quantities related to the scattered and the internal field can be expressed in terms of Eqs. (1.33) and (1.34).

As discussed in Section 1.1, the optical properties of a particle are codified into the scattering, absorption and extinction cross sections, quantities that can be calculated by means of the scattering amplitude matrix [Eq. (1.1)] and the Optical Theorem [Eq. (1.12)]. Since the particle is spherical, it is convenient to exploit the symmetry of the problem by decomposing the scattered electric field [Eq. (1.28a)] into components parallel and perpendicular to the scattering plane. To obtain the scattering amplitude matrix expressed in an orthogonal base relative to the scattering plane ($\hat{\mathbf{e}}_s^s = \hat{\mathbf{e}}_\theta$ and $\hat{\mathbf{e}}_s^s = -\hat{\mathbf{e}}_\varphi$) let us substitute the Mie Coefficients [Eq. (1.33)] into Eq. (1.28a) while rewriting the VSH $\mathbf{M}_{o1\ell}^{(3)}$ [Eq. (1.23b)] and $\mathbf{N}_{e1\ell}^{(3)}$ [Eq. (1.22c)] in terms of the Riccati-Bessel function ξ and its derivative:

$$\mathbf{E}^{sca} \cdot \hat{\mathbf{e}}_r = \frac{\cos \varphi}{(kr)^2} \sum_{\ell}^{\infty} E_0 i^\ell (2\ell + 1) i a_\ell \xi(kr) \pi_\ell(\theta) \sin \theta, \quad (1.35)$$

$$\mathbf{E}^{sca} \cdot \hat{\mathbf{e}}_s^s = \frac{\cos \varphi}{kr} \sum_{\ell}^{\infty} E_0 i^\ell \frac{2\ell + 1}{\ell(\ell + 1)} [i a_\ell \xi'_\ell(kr) \tau_\ell(\theta) - b_\ell \xi_\ell(kr) \pi_\ell(\theta)], \quad (1.36)$$

$$\mathbf{E}^{sca} \cdot \hat{\mathbf{e}}_s^s = \frac{\sin \varphi}{-kr} \sum_{\ell}^{\infty} E_0 i^\ell \frac{2\ell + 1}{\ell(\ell + 1)} [i a_\ell \xi'_\ell(kr) \pi_\ell(\theta) - b_\ell \xi_\ell(kr) \tau_\ell(\theta)]. \quad (1.37)$$

The scattering amplitude matrix relates the incident electric field to the scattered electric field in the far field regime, that is when $kr \gg 1$. Considering that the series of Eqs. (1.35)-(1.37) converge uniformly, so all contributions after the sufficiently large term ℓ_c of the sum can be neglected for all values of kr , the asymptotic expressions for the ξ Riccati-Bessel function and its derivative can be employed, which are [2]

$$\xi(kr) \approx (-i)^\ell \frac{\exp(ikr)}{i}, \quad \text{and} \quad \frac{d\xi(kr)}{d(kr)} = (-i)^\ell \exp(ikr) \left(\frac{1}{ikr} + 1 \right), \quad \text{when } \ell_c^2 \ll kr. \quad (1.38)$$

1.2 Mie Scattering

Substituting Eq. (1.38) into Eqs. (1.35)-(1.37) and depreciating all terms proportional to $(kr)^{-2}$ it leads to a zero radial electric field while

$$\mathbf{E}^{\text{sca}} \cdot \hat{\mathbf{e}}_{\parallel}^{\text{sca}} \approx \frac{\exp(ikr)}{r} \left\{ \frac{i}{k} \sum_{\ell}^{\infty} \frac{2\ell+1}{\ell(\ell+1)} [a_{\ell}\tau_{\ell}(\cos \theta) + b_{\ell}\pi_{\ell}(\cos \theta)] \right\} E_0 \cos \varphi, \quad (1.39)$$

$$\mathbf{E}^{\text{sca}} \cdot \hat{\mathbf{e}}_{\perp}^{\text{sca}} \approx \frac{\exp(ikr)}{r} \left\{ \frac{i}{k} \sum_{\ell}^{\infty} \frac{2\ell+1}{\ell(\ell+1)} [a_{\ell}\pi_{\ell}(\cos \theta) + b_{\ell}\tau_{\ell}(\cos \theta)] \right\} E_0 (-\sin \varphi), \quad (1.40)$$

where it can be identified that $\mathbf{E}^{\text{i}} \cdot \hat{\mathbf{e}}_{\parallel}^{\text{i}} = E_0 \cos \varphi$ and $\mathbf{E}^{\text{i}} \cdot \hat{\mathbf{e}}_{\perp}^{\text{i}} = -E_0 \sin \varphi$ for \mathbf{E}^{i} a plane wave traveling along the z direction with an arbitrary polarization. Finally, the Scattering Amplitude Matrix for a spherical particle can be obtained by comparing Eqs. (1.39) and (1.40) with Eq. (1.1), leading to

Scattering Amplitude Matrix for Spherical Particles

$$\mathbb{F}(\hat{\mathbf{k}}^{\text{sca}}, \hat{\mathbf{k}}^{\text{i}}) = \begin{pmatrix} \frac{i}{k} S_2(\theta) & 0 \\ 0 & \frac{i}{k} S_1(\theta) \end{pmatrix}, \quad (1.41)$$

with $\hat{\mathbf{k}}^{\text{sca}} = \hat{\mathbf{e}}_r$, $\hat{\mathbf{k}}^{\text{i}} = \hat{\mathbf{e}}_z$, $\cos \theta = \hat{\mathbf{k}}^{\text{sca}} \cdot \hat{\mathbf{k}}^{\text{i}}$ and

$$S_1(\theta) = \sum_{\ell}^{\infty} \frac{2\ell+1}{\ell(\ell+1)} [a_{\ell}\tau_{\ell}(\cos \theta) + b_{\ell}\pi_{\ell}(\cos \theta)], \quad (1.42)$$

$$S_2(\theta) = \sum_{\ell}^{\infty} \frac{2\ell+1}{\ell(\ell+1)} [a_{\ell}\pi_{\ell}(\cos \theta) + b_{\ell}\tau_{\ell}(\cos \theta)]. \quad (1.43)$$

1.2.3 Au Spherical NPs

Falta emplear las relacinoes de ortogonalidad para calcular las secciones de extincion y edmás

1. OPTICAL PROPERTIES OF SINGLE PLASMONIC NANOPARTICLES

In Fig. 1.2 the extinction Q_{ext} and the scattering Q_{sca} efficiencies of a gold NP (AuNP) with a radius of $a = 12.5$ nm are shown as function of the wavelength λ of the incident planewave illuminating the NP. Two matrices were considered in Fig. 1.2: a matrix of air with a refractive index of $n_{\text{mat}} = 1$ (black lines) and a matrix of glass with $n_{\text{mat}} = 1.5$ (orange lines). The experimental dielectric function for Au reported by Johnson and Christy [10] was employed to model the electromagnetic response of the spherical AuNP nevertheless, this data corresponds to a bulk sample, meaning that it may not reproduce the optical behavior of a NP since surface effects cease to be neglectable due to their spacial dimensions [11]. In order to study the optical properties of AuNP while considering surface effects, a size correction to the dielectric function of the AuNP was performed as described in Appendix A. The efficiencies of the 12.5 nm AuNP taking into account a dielectric function with (dashed lines) and without (solid lines) a size correction were compared for both considered matrices; on each curve the wavelength of their maximum value is indicated.

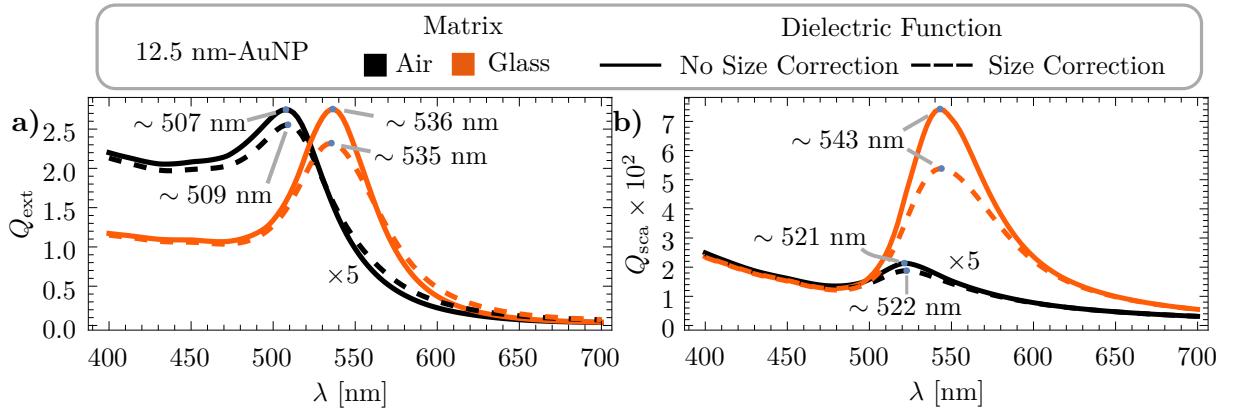


Fig. 1.2: a) Extinction Q_{ext} and b) Scattering Q_{sca} efficiencies of a 12.5 nm Au spherical NP embedded into a vacuum-like matrix (black, $n_{\text{mat}} = 1$) and into a water-like matrix (orange, $n_{\text{mat}} = 1.33$), as function of the wavelength λ of the incident plane wave. The solid curves were calculated by considering no size effects on the dielectric function of the AuNP, while the dashed curves consider a size correction to it; the experimental data of Johnson and Christy [10] was employed.

From the extinction and scattering efficiencies in Fig. 1.2, two main spectral tendencies arises between these quantities: on the overall value of the efficiencies and on the spectral position of their maximum. Since the scattering efficiency is two orders of magnitude smaller than the extinction efficiency within the visible range, the main energy loss mechanism is absorption, as stated by the Optical Theorem [Eq. (1.12)]. Even though the 12.5 nm AuNP absorbs more light than what it scatters, both phenomena are present. For example, when the studied AuNP is embedded in air, the wavelengths at which it absorbs and scatters the most are ~ 509 nm and ~ 522 nm, respectively. When the AuNP is embedded into glass, the absorption of light is optimized at a wavelength of ~ 535 nm, while the scattering is optimized at ~ 543 nm. For both an air and a glass matrix, the wavelength of most scattering is redshifted relative to the wavelength of most absorption: ~ 15 nm for air and ~ 7 nm for glass. The extinction and scattering have different spectral tendencies as already discussed, yet they share common characteristics when the dependency on the embedding media is studied.

Both the scattering and the absorption efficiencies of a 12.5 nm AuNP present an overall enhancement within the visible range when the refractive index of the matrix, the embedding media, increases. This can be seen in Fig. 1.2 by comparing the black curves ($n_{\text{mat}} = 1$) with the orange curves ($n_{\text{mat}} = 1.5$). The maximum value of the extinction efficiency of a 12.5 nm AuNP

for a matrix of glass is around five times bigger than for a matrix of air, as it can be seen in Fig. 1.3a), while the maximum value of the scattering efficiency for a glass matrix is around eighth times bigger compared to the case of an air matrix, as shown in Fig. 1.3b). The enhancement of the scattering efficiency as function of the refractive index of the matrix can be understood by analyzing the size parameter $x = (2\pi/\lambda)an_{\text{mat}}$, which compares the size of the NP relative to the incident wavelength in the matrix: the larger the value of x , the bigger a NP can be considered inside such matrix. Since the size parameter is a linear function of n_{mat} , the AuNP embedded into glass will behave more like a bigger NP, thus having a more significant contribution from the scattering to the light extinction mechanism inside glass than inside air.

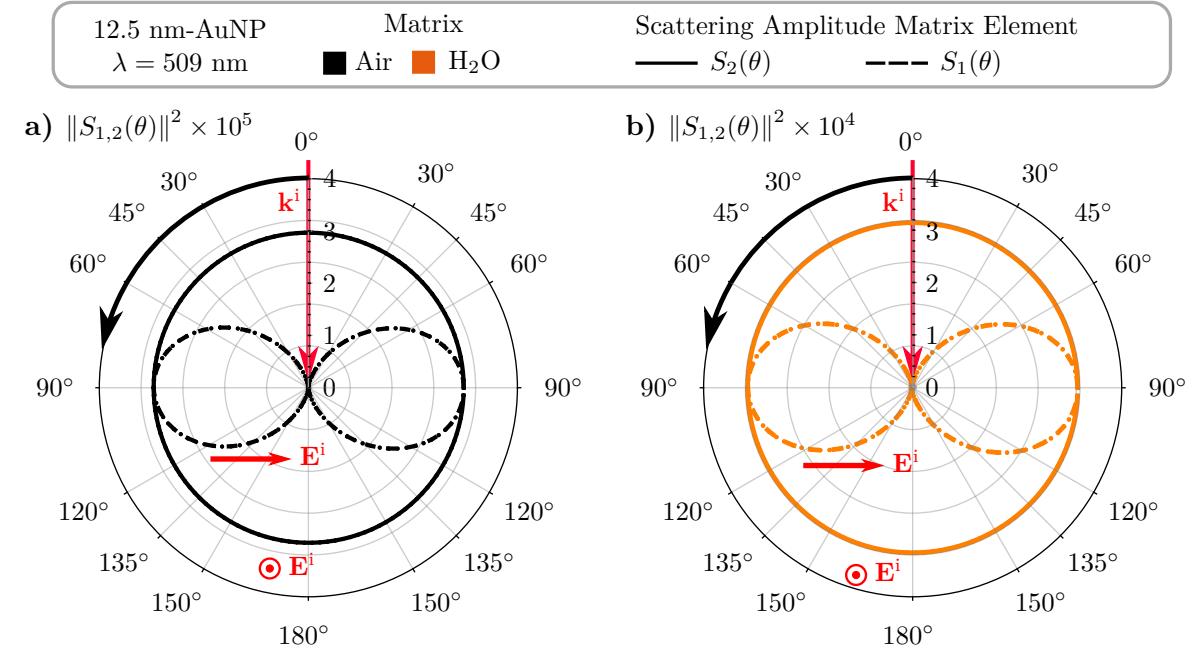


Fig. 1.3: a) Extinction Q_{ext} and b) Scattering Q_{sca} efficiencies of a 12.5 nm Au spherical NP embedded into a vacuum-like matrix (black, $n_{\text{mat}} = 1$) and into a water-like matrix (orange, $n_{\text{mat}} = 1.33$), as function of the wavelength λ of the incident plane wave. The solid curves were calculated by considering no size effects on the dielectric function of the AuNP, while the dashed curves consider a size correction to it; the experimental data of Johnson and Christy [10] was employed.

The Finite Element Method

2.1 Finite Element Method and Analytical Solutions

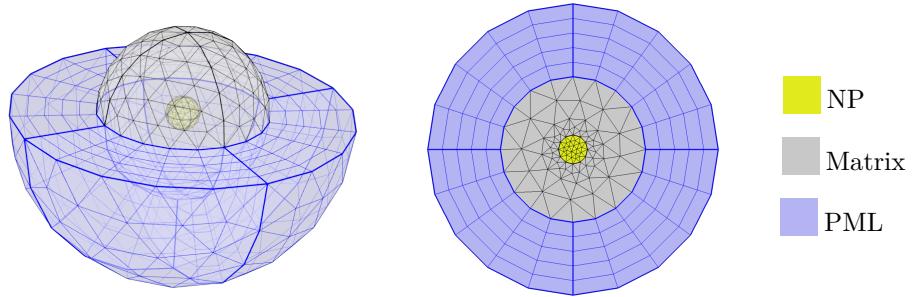


Fig. 2.1: A 3D view (left) and the cross section (right) of a spherical symmetric COMSOL setup to calculate the optical response of a single spherical NP embedded into a matrix. The NP (yellow) is located at the center of the matrix (gray), which is covered by a PML layer (blue). The upper layer of the PML is hidden to allow a better view of the setup.

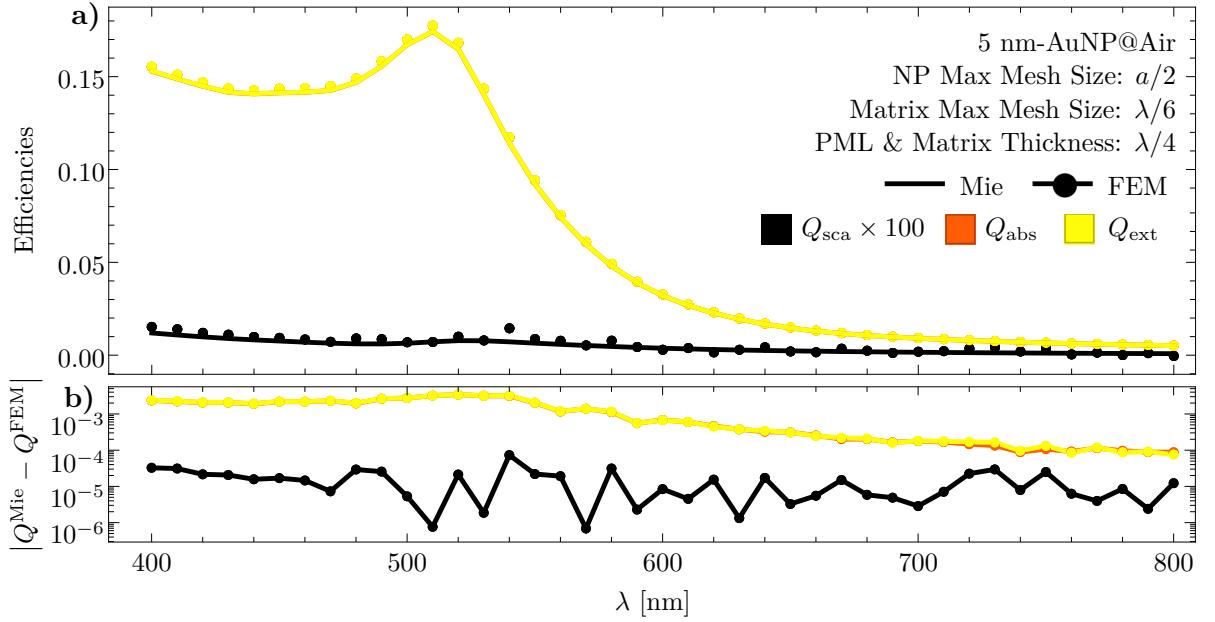


Fig. 2.2: a) Scattering Q_{sca} , absorption Q_{abs} and extinction Q_{ext} efficiencies of a 5 nm AuNP embedded into air calculated by means of the Mie Theory (continuous) and the FEM (disks), and b) their absolute error, as function of the wavelength λ of the incident planewave. The chosen parameters for the FEM calculations were based on the COMSOL Excercises **CITAR**.

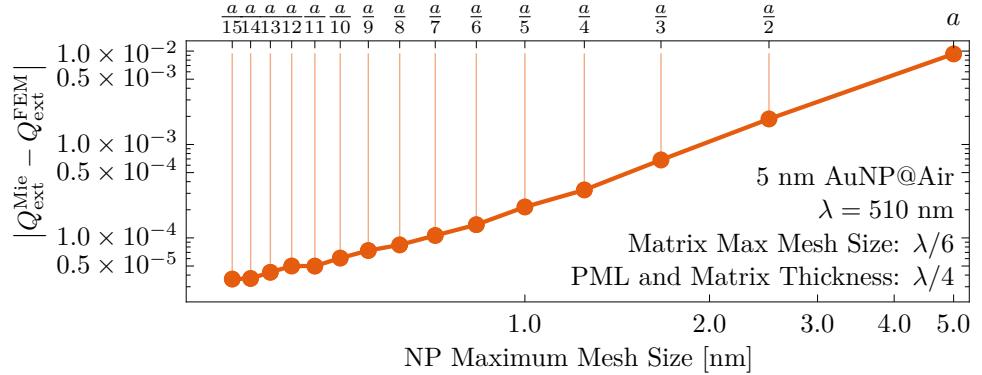


Fig. 2.3: Absolute error between the Mie Theory and the FEM calculation on the extinction efficiency Q_{ext} of a 5nm AuNP@Air as function of the maximum mesh size within the NP at the wavelength of the LSPR.

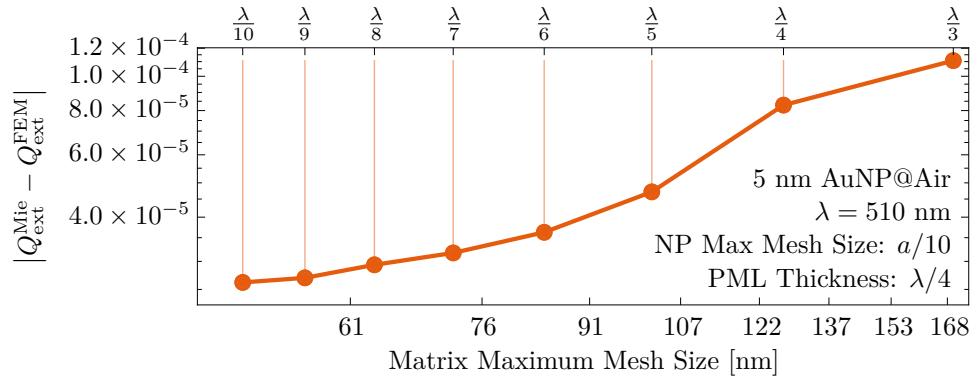


Fig. 2.4: Absolute error between the Mie Theory and the FEM calculation on the extinction efficiency Q_{ext} of a 5nm AuNP@Air as function of the maximum mesh size within the matrix at the wavelength of the LSPR.

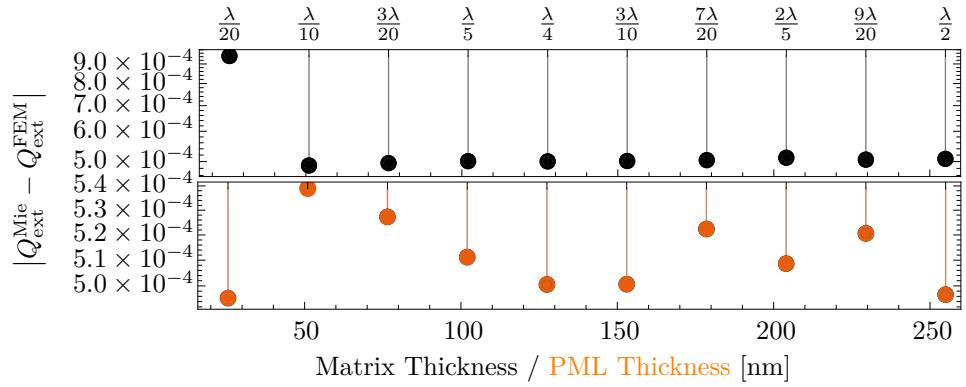


Fig. 2.5: Absolute error between the Mie Theory and the FEM calculation on the extinction efficiency Q_{ext} of a 5nm AuNP@Air as function of the matrix thickness (black) and the PML thickness (orange) at the wavelength of the LSPR. It was chosen for both cases a NP maximum mesh size of $a/10$ and a matrix maximum mesh size of $\lambda/6$; the default thickness of the matrix and PML was set to $\lambda/4$.

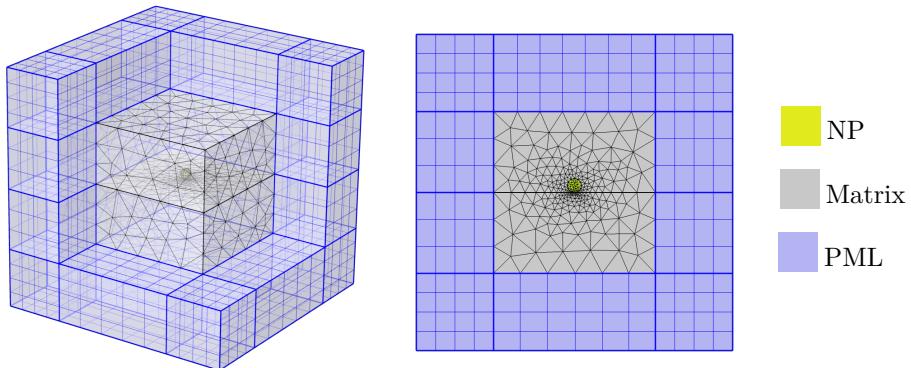


Fig. 2.6: A 3D view (left) and the cross section (right) of a spherical symmetric COMSOL setup to calculate the optical response of a single spherical NP embedded into a matrix. The NP (yellow) is located at the center of the matrix (gray), which is covered by a PML layer (blue). The upper layer of the PML is hidden to allow a better view of the setup.

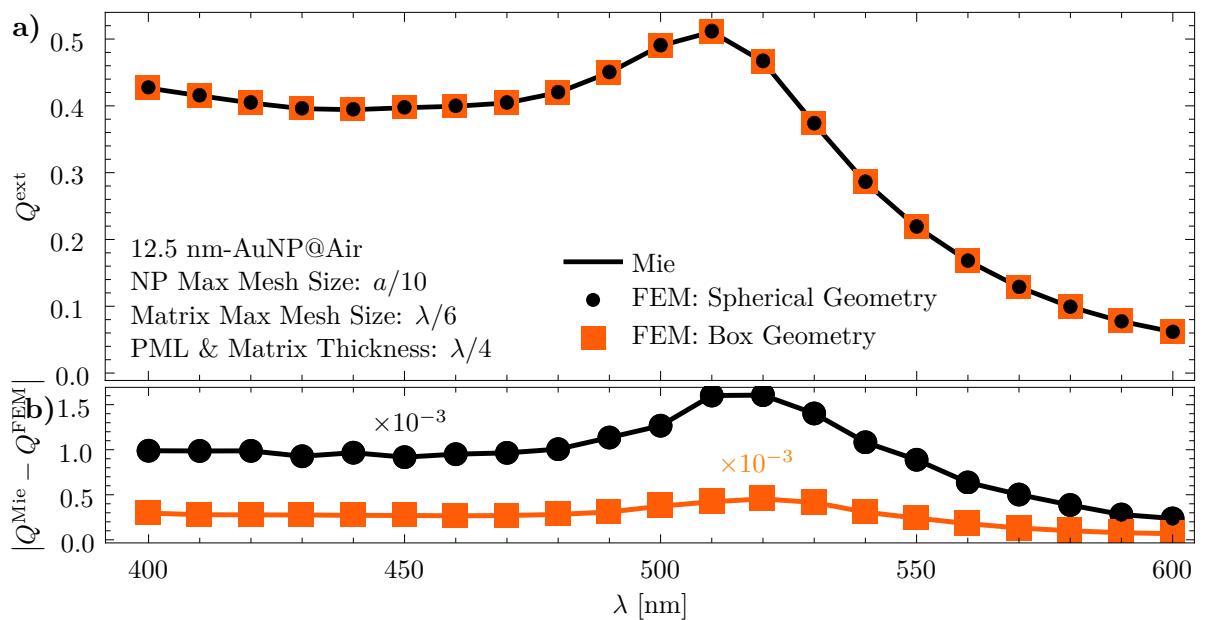


Fig. 2.7: a) Scattering Q_{sca} , absorption Q_{abs} and extinction Q_{ext} efficiencies of a 5 nm AuNP embedded into air calculated by means of the Mie Theory (continuous) and the FEM (disks), and b) their absolute error, as function of the wavelength λ of the incident planewave. The chosen parameters for the FEM calculations were based on the COMSOL Exercises **CITAR**.

Chapter 3

Results and Discussion

3.1 Incrustation Degree of a Spherical Particle

3.2 Supported Nanoparticles

3.3 Incrustaded Nanoparticles

3.4 Future Work: Application on Metasurfaces

3. RESULTS AND DISCUSSION

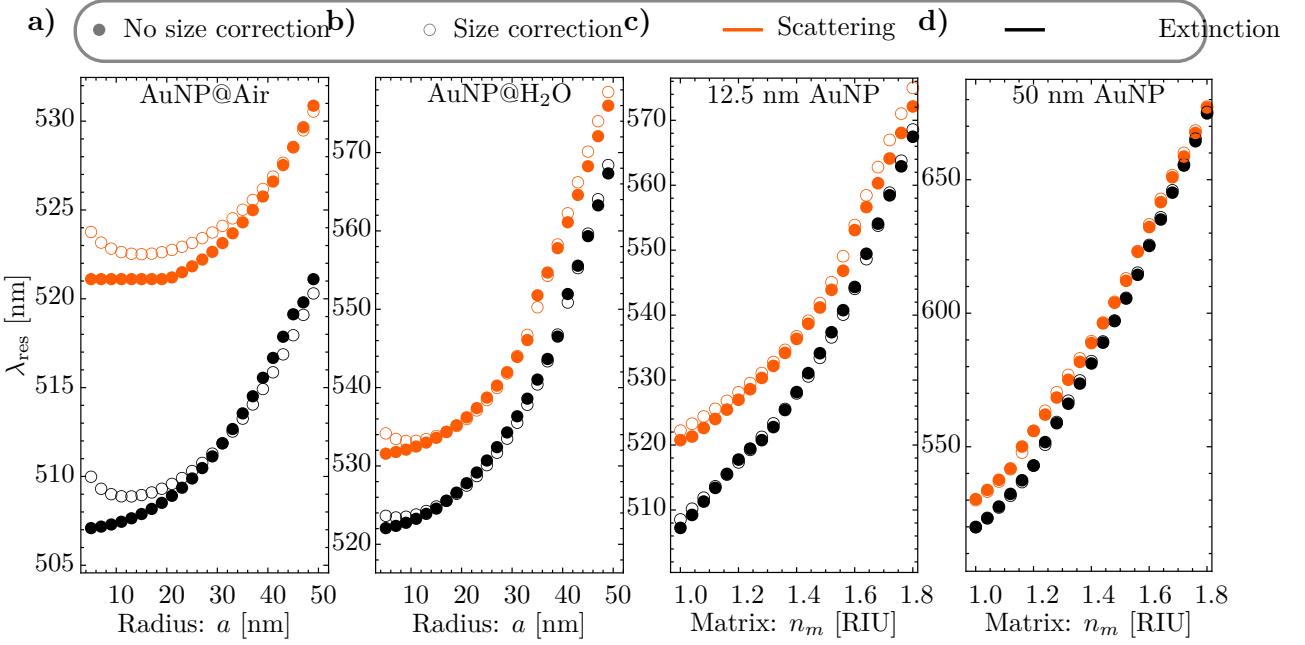


Fig. 3.1: Resonance wavelength (λ_{res}) of the scattering (orange) and extinction (black) cross sections as functions of the NPs radii when embedded 3.1a) into air and 3.1b) into water, and as function of the refractive index of the matrix for NP of radius set to 3.1c) 12.5 nm and 3.1d) 50 nm.

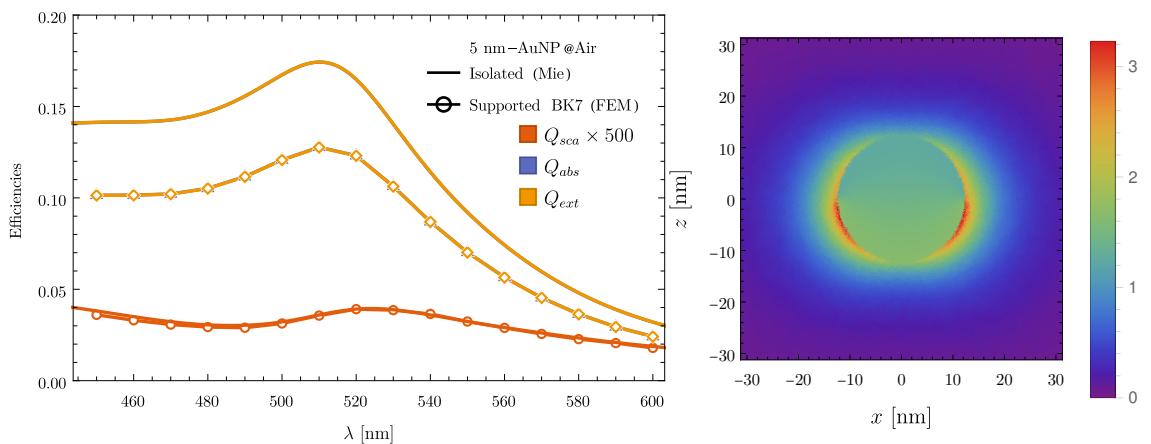


Fig. 3.2: Resonance wavelength (λ_{res}) of the scattering (orange) and extinction (black) cross sections as functions of the NPs radii when embedded 3.1a) into air and 3.1b) into water, and as function of the refractive index of the matrix for NP of radius set to 3.1c) 12.5 nm and 3.1d) 50 nm.

3.4 Future Work: Application on Metasurfaces

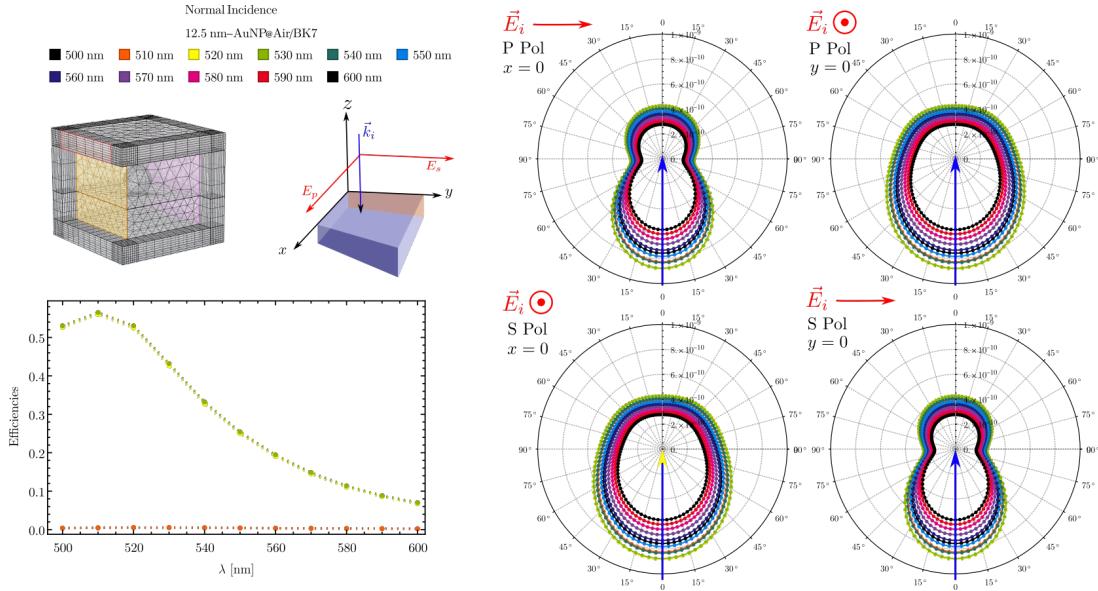


Fig. 3.3: Resonance wavelength (λ_{res}) of the scattering (orange) and extinction (black) cross sections as functions of the NPs radii when embedded 3.1a) into air and 3.1b) into water, and as function of the refractive index of the matrix for NP of radius set to 3.1c) 12.5 nm and 3.1d) 50 nm.

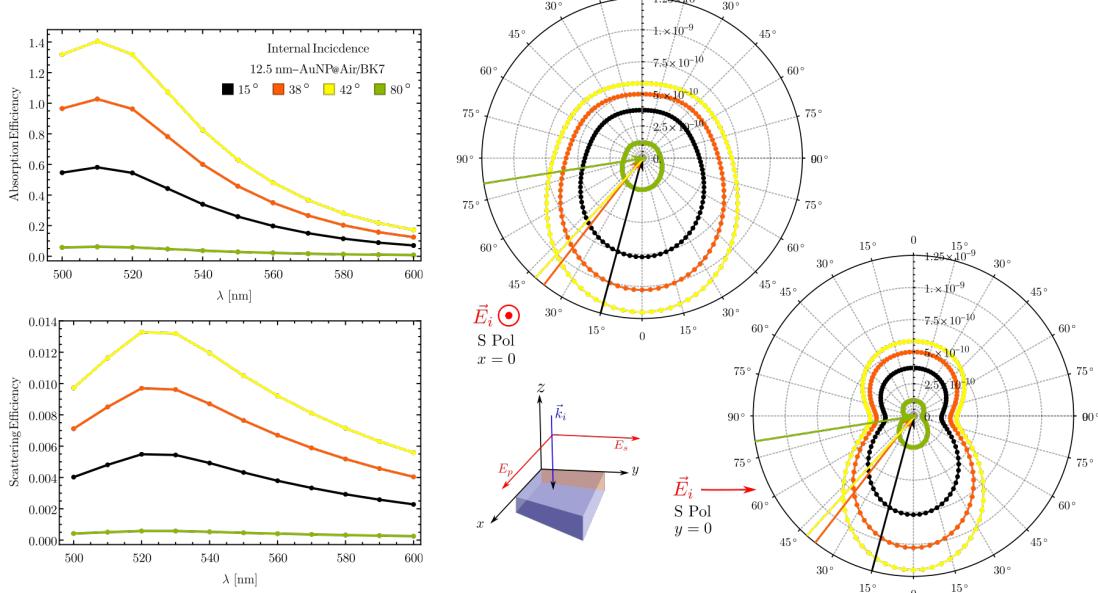


Fig. 3.4: Resonance wavelength (λ_{res}) of the scattering (orange) and extinction (black) cross sections as functions of the NPs radii when embedded 3.1a) into air and 3.1b) into water, and as function of the refractive index of the matrix for NP of radius set to 3.1c) 12.5 nm and 3.1d) 50 nm.

3. RESULTS AND DISCUSSION

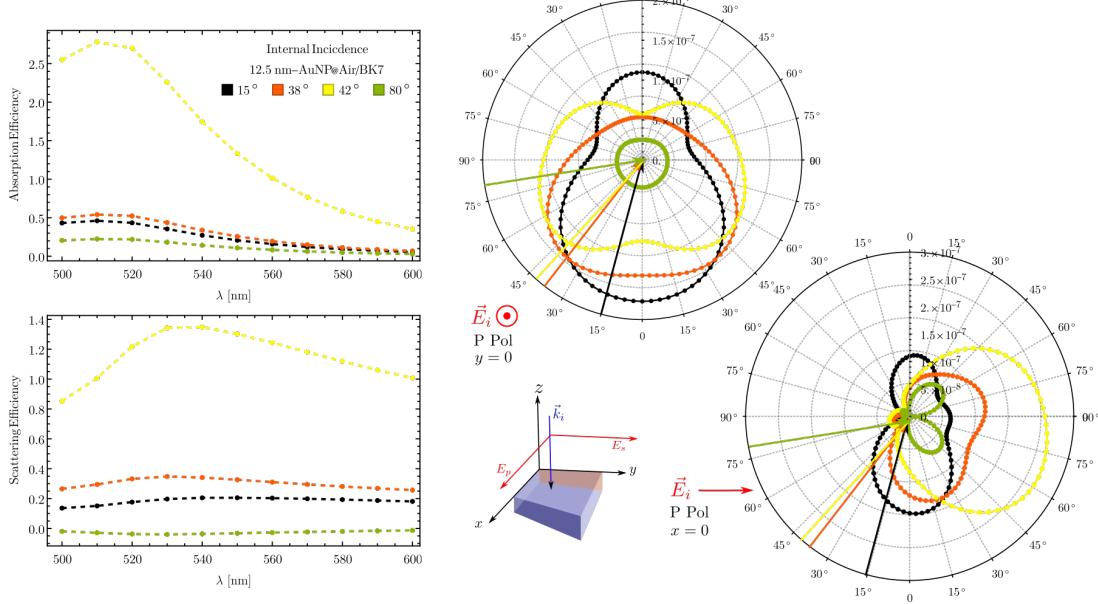


Fig. 3.5: Resonance wavelength (λ_{res}) of the scattering (orange) and extinction (black) cross sections as functions of the NPs radii when embedded 3.1a) into air and 3.1b) into water, and as function of the refractive index of the matrix for NP of radius set to 3.1c) 12.5 nm and 3.1d) 50 nm.

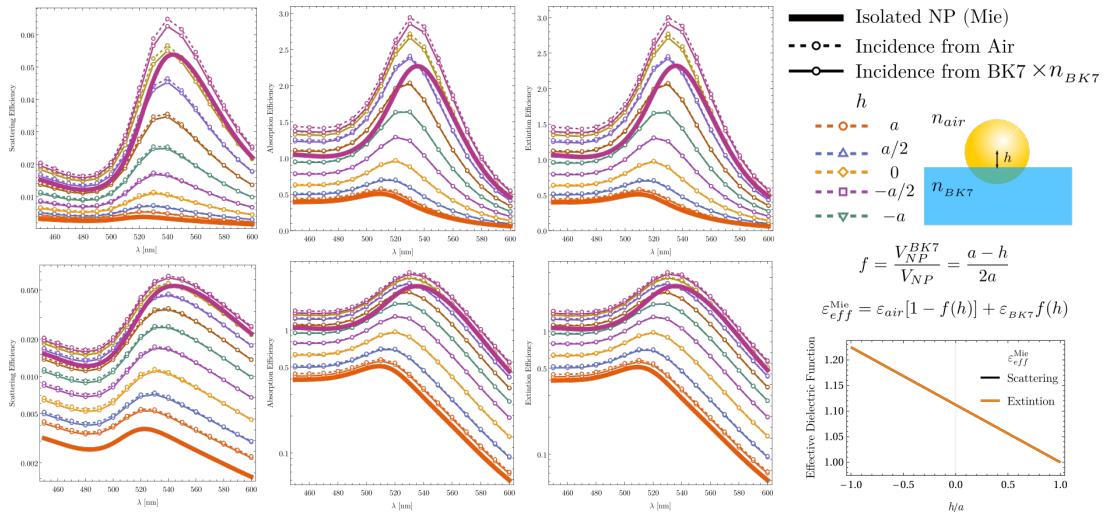


Fig. 3.6: Resonance wavelength (λ_{res}) of the scattering (orange) and extinction (black) cross sections as functions of the NPs radii when embedded 3.1a) into air and 3.1b) into water, and as function of the refractive index of the matrix for NP of radius set to 3.1c) 12.5 nm and 3.1d) 50 nm.

Chapter 4

Conclusions

Appendix A

Size Corrected Dielectric Function

In this work, the optical properties of spherical gold (Au) nanoparticles (NPs) with radius $a = 12.5$ nm were studied. Even though the optical response of a non magnetic material is codified into the dielectric function $\varepsilon(\omega)$, the dielectric function for materials at the nanoscale differs from those in bulk due to surface effects. To perform a size correction to the dielectric function, let us decompose it into two additive contributions arising from intra- and interband electronic transitions [11]. If no spacial dispersion is considered, the intraband contribution of the dielectric function can be described by means of the Drude-Sommerfeld model

$$\frac{\varepsilon_{\text{Drude}}(\omega)}{\varepsilon_0} = 1 - \frac{\omega_p^2}{\omega(\omega + i\gamma)}, \quad (\text{A.1})$$

where ε_0 is the vacuum permittivity, and ω_p is the plasma frequency and γ the damping constant. In general, the damping constant is inversely proportional to the average time between collision events of the electrons inside the material and its value depends on the material itself and on its the geometry and dimensions. For example, the damping constant for a material in bulk γ^{Bulk} equals v_F/L with v_F the Fermi velocity and L the mean free path of the electrons. On the other hand, the damping constant γ_a^{NP} for a spherical NP of radius a deviates from γ^{Bulk} if the mean free path is greater than the size of the NP ($L > 2a$), in which case an effective mean free path replaces L , leading to the following expression for the damping constant:

$$\gamma_a^{\text{NP}} = \gamma^{\text{Bulk}} + A \frac{v_F}{a}, \quad \text{with} \quad \gamma^{\text{Bulk}} = \frac{v_F}{L}, \quad (\text{A.2})$$

where A is a theory dependent parameter whose exact value changes according to the approach employed to calculate the effective mean free path; for this work it is considered that $A = 1$.

In practice, the experimental data for the dielectric function of a material $\varepsilon_{\text{Exp}}(\omega)$ corresponds to a material in bulk, so a size correction is performed on $\varepsilon_{\text{Exp}}(\omega)$ if the optical properties of NPs are studied. The size correction is done by subtracting the intraband contribution that best fits the experimental bulk data and adding an intraband contribution considering Eq. (A.2), that is, the size corrected dielectric function $\varepsilon_{\text{Size}}(\omega)$ is given by

$$\frac{\varepsilon_{\text{Size}}(\omega)}{\varepsilon_0} = \frac{\varepsilon_{\text{Exp}}(\omega)}{\varepsilon_0} + \left(-\frac{\varepsilon_{\text{Drude}}(\omega)}{\varepsilon_0} \Big|_{\gamma=\gamma^{\text{Bulk}}} + \frac{\varepsilon_{\text{Drude}}(\omega)}{\varepsilon_0} \Big|_{\gamma=\gamma_a^{\text{NP}}} \right), \quad (\text{A.3})$$

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The size correction in Eq. (A.3) considers the size effects on the intraband contribution of the dielectric function while the size corrections due to the interband contributions are neglected since it has been reported that they are relevant for NPs with radii smaller than 2 nm [12].

To employ the size corrected dielectric function [Eq. (A.3)], the parameters ω_p and γ^{Bulk} that best fit $\varepsilon_{\text{Exp}}(\omega)$ are needed. Let us develop two linear relations involving ω_p and γ^{Bulk} and the real and imaginary parts of $\varepsilon_{\text{Drude}}(\omega)$ following the method from Mendoza Herrera, Arboleda, Schinca, and Scaffardi. The real and imaginary parts of $\varepsilon_{\text{Drude}}(\omega)$ are

$$\text{Re} \left[\frac{\varepsilon_{\text{Drude}}(\omega)}{\varepsilon_0} \right] = 1 - \frac{\omega_p^2 \omega^2}{\omega^4 + (\omega \gamma)^2}, \quad \text{and} \quad \text{Im} \left[\frac{\varepsilon_{\text{Drude}}(\omega)}{\varepsilon_0} \right] = \frac{\omega_p^2 (\omega \gamma)}{\omega^4 + (\omega \gamma)^2}. \quad (\text{A.4})$$

according to Eq. (A.1). By multiplying the imaginary part of $\varepsilon_{\text{Drude}}(\omega)$ by ω and comparing it with its real part, one obtains that

$$\omega \text{Im} \left[\frac{\varepsilon_{\text{Drude}}(\omega)}{\varepsilon_0} \right] = \gamma \left(1 - \text{Re} \left[\frac{\varepsilon_{\text{Drude}}(\omega)}{\varepsilon_0} \right] \right), \quad (\text{A.5})$$

and in a similar manner it can be verified that

$$\omega^2 \left\{ \text{Im} \left[\frac{\varepsilon_{\text{Drude}}(\omega)}{\varepsilon_0} \right]^2 + \left(1 - \text{Re} \left[\frac{\varepsilon_{\text{Drude}}(\omega)}{\varepsilon_0} \right] \right)^2 \right\} = \omega_p^2 \left(1 - \text{Re} \left[\frac{\varepsilon_{\text{Drude}}(\omega)}{\varepsilon_0} \right] \right). \quad (\text{A.6})$$

By plotting the left hand side of Eqs. (A.5) and (A.6) as a function of $1 - \text{Re}[\varepsilon_{\text{Drude}}(\omega)/\varepsilon_0]$ and fitting two linear functions, the values for γ and ω_p^2 can be calculated according to the right hand side of Eqs. (A.5) and (A.6), respectively. As a final remark, the experimental dielectric

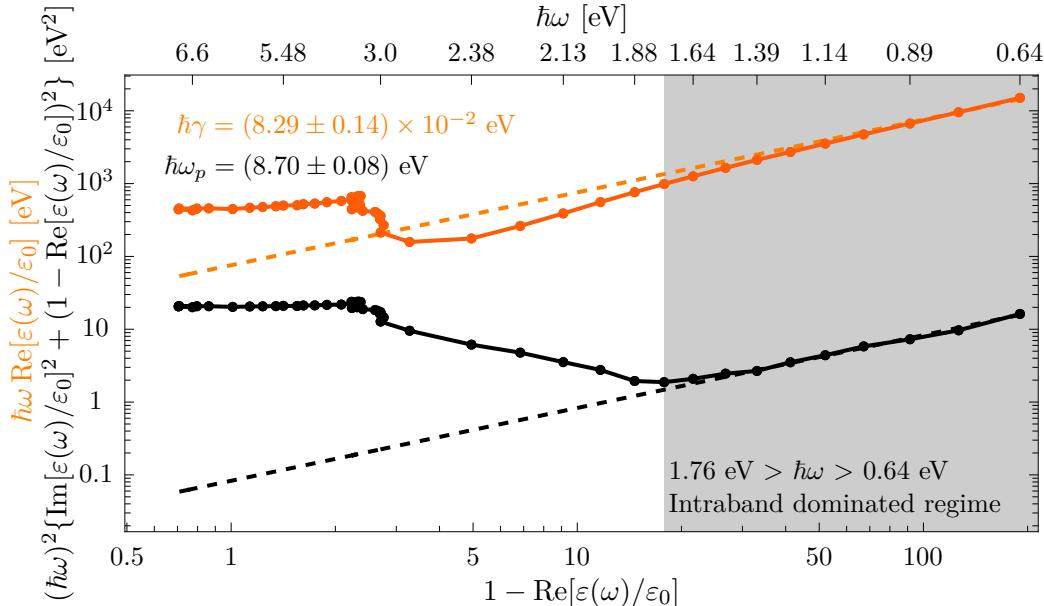


Fig. A.1: Plot of Eqs. (A.5) (orange) and (A.6) (black) evaluated with the experimental dielectric function reported by Johnson and Christy [10]. The shaded region corresponds to the frequency window from 0.64 eV to 1.76 eV, which is best described by the Drude-Sommerfeld model and which was considered to perform the linear fits (dashed), determining a plasma frequency of $\hbar\omega_p = (8.70 \pm 0.08)$ eV and a damping constant of $\hbar\gamma = (8.29 \pm 0.14) \times 10^{-2}$ eV for Au.

function includes both an intra- and an interband contribution while Eqs. (A.5) and (A.6) are only valid for the intraband contribution of the dielectric function, thus the linear fits should be done within a spectral window into which the interband contributions are negligible compared to the Drude-Sommerfeld model, which best describes the optical properties of a material when $\omega \rightarrow 0$. The choice of the spectral window for the experimental data fit of the dielectric function can modify the calculated values of γ and ω_p .

In Fig. A.1, the left hand side of Eqs. (A.5) and (A.6) are plotted in orange and black, respectively, as a function of $1 - \text{Re}[\varepsilon(\omega)/\varepsilon_0]$, where $\varepsilon(\omega)$ corresponds to the experimental data of the dielectric function of Au (markers) reported by Johnson and Christy [10]; to ease the read of Fig. A.1, continuous lines between the data were added as a guide to the eye and the photon energy $\hbar\omega$ of selected points of the experimental data are shown on the top margin. The shaded region in Fig. A.1 is the frequency window $0.64 \text{ eV} < \hbar\omega < 1.76 \text{ eV}$, into which the experimental data for Au shows a linear behavior as stated by Eqs.(A.5) and (A.6), that is, within this interval the intraband contribution to the dielectric function is dominant, thus the linear fits (dashed lines) were made with the data in this region, determinating a plasma frequency of $\hbar\omega_p = (8.70 \pm 0.08) \text{ eV}$ and a damping constant of $\hbar\gamma = (8.29 \pm 0.14) \times 10^{-2} \text{ eV}$ for Au in bulk. Once the plasma frequency and the damping constant for Au have been obtained, the size corrected dielectric for spheres can be calculated.

The real part (blue) and imaginary part (red) of the size corrected dielectric function for Au, based in the experimental data from Johnson and Christy, is plotted in Fig. A.2 as function of the photon energy $\hbar\omega$; on the top margin it is shown the conversion of the photon energy into wavelength λ . The size corrected dielectric function was calculated for several cases: Au in bulk

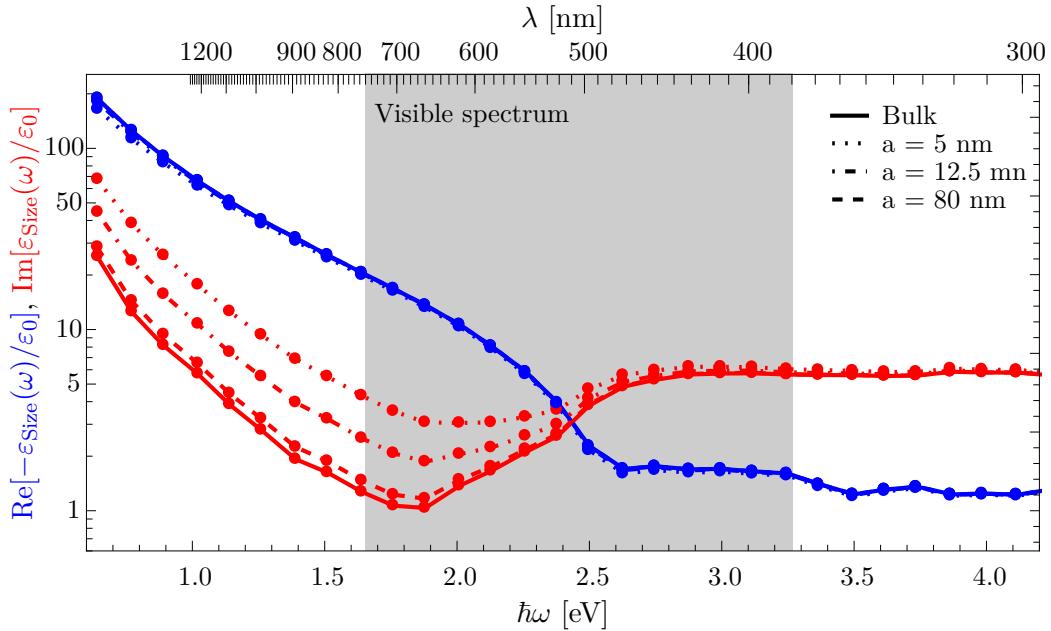


Fig. A.2: Real (blue) and imaginary (red) parts of the size corrected dielectric function of Au in bulk (continuous lines) and of spherical Au NPs of radius 5 nm (dotted lines), 12.5 nm (dash dotted lines) and 80 nm (dashed lines), as function of the photon energy $\hbar\omega$ (wavelength λ). The size corrected dielectric function was calculated from the experimental data of Johnson and Christy [10].

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(continuous lines) and spherical Au NPs of radius 5 nm (dotted lines), 12.5 nm (dash dotted lines) and 80 nm (dashed lines); all lines are guides to the eye. The data in Fig. A.2 shows that the need for a size corrected dielectric functions increases as the frequency decreases (wavelength decreases), specifically for the visible spectrum (shaded region) the size correction is appreciated for $\hbar\omega < 2.5$ eV ($\lambda > 500$ nm). From Fig. A.2 it can also be seen that the imaginary part of the size corrected dielectric function differs the most from the bulk dielectric function compared to its real part, whose deflection from the bulk optical response are barely visible near $\hbar\omega \approx 1$ eV.

Appendix B

Mie Theory (Conventions and Code)

The Vector Spherical Harmonics (VSH) were defined in Sec. 1.2.1 in terms of their generating function $\psi(r, \theta, \varphi)$ which must satisfy the scalar Helmholtz equation [Eq. (1.15)]. By employing the separation of variables method, it was determined that ψ is the product of either $\sin(m\varphi)$ or $\cos(m\varphi)$, of the associated Legendre functions $P_\ell^m(\cos\theta)$ and the spherical Bessel/Hankel functions $z_\ell(kr)$, all of which are solutions to Eqs. (1.16)-(1.20). In this section, it is discussed the chosen definitions for P_ℓ^m , z_ℓ and related functions, as well as how to calculate them. It is also detailed how to code the Mie Theory results employing the Wolfram Language.

Radial Dependency: Spherical Bessel/Hankel Functions

The radial dependency of the VSH is given by the two linearly independent solutions to Eq. (1.20) which are the spherical Bessel function of first and second kind $j_\ell(\rho)$ and $y_\ell(\rho)$, respectively, related by the regular Bessel function of fractional order $J_{\ell+1/2}(\rho)$ and $Y_{\ell+1/2}(\rho)$ by

$$j_\ell(\rho) = \sqrt{\frac{\pi}{2\rho}} J_{\ell+1/2}(\rho), \quad \text{and} \quad y_\ell(\rho) = \sqrt{\frac{\pi}{2\rho}} Y_{\ell+1/2}(\rho). \quad (\text{B.1})$$

Another set of two linear independent solutions to Eq. (1.20) are the spherical Hankel functions of first ($h_\ell^{(1)}$) and second kind ($h_\ell^{(2)}$) given by

$$h_\ell^{(1)}(\rho) = j_\ell(\rho) + iy_\ell(\rho), \quad \text{and} \quad h_\ell^{(2)}(\rho) = j_\ell(\rho) - iy_\ell(\rho). \quad (\text{B.2})$$

Since the spherical Hankel functions are a linear combination of the Bessel spherical functions, they four obey the following recurrence relations

$$\frac{z_\ell(\rho)}{\rho} = \frac{z_{\ell-1}(\rho) + z_{\ell+1}(\rho)}{2\ell + 1}, \quad (\text{B.3})$$

$$\frac{dz_\ell(\rho)}{d\rho} = \frac{\ell z_{\ell-1}(\rho) - (\ell + 1)z_{\ell+1}(\rho)}{2\ell + 1}, \quad (\text{B.4})$$

with z_ℓ any of the functions in Eqs. (B.1) and (B.2).

Azimuthal Angular Dependency φ : Sine, Cosine

Within this text, it was chosen the azimuthal solution to the scalar Helmholtz equation to be sines and cosines, so m can only take non negative integer values. These functions obey the orthogonality relations

$$\int_0^{2\pi} \sin(m\varphi) \sin(m'\varphi) d\varphi = \delta_{m,m'}(1 - \delta_{0,m})\pi, \quad (\text{B.5})$$

$$\int_0^{2\pi} \cos(m\varphi) \cos(m'\varphi) d\varphi = \delta_{m,m'}(1 + \delta_{0,m})\pi, \quad (\text{B.6})$$

$$\int_0^{2\pi} \cos(m\varphi) \sin(m'\varphi) d\varphi = 0, \quad (\text{B.7})$$

with $\delta_{m,m'}$ the Kronecker delta.

Polar Angular Dependency: Associated Legendre Functions and the Angular Functions π_ℓ and τ_ℓ

The solution to the polar angle equation are the associated Legendre functions and in this work they are defined as by Arfken and Weber [13], that is,

$$P_\ell^m(\mu) = (1 - \mu^2)^{m/2} \frac{d^m}{d\mu^m} P_\ell(\mu), \quad \text{with} \quad P_\ell(\mu) = \frac{1}{2^\ell \ell!} \frac{d^\ell}{d\mu^\ell} (\mu^2 - 1)^\ell, \quad (\text{B.8})$$

where $\mu = \cos \theta$ and $P_\ell(\mu)$ are the Legendre polynomials with ℓ a non negative integer. With such definition, the associated Legendre functions follows the orthogonality relation

$$\int_{-1}^1 P_\ell^m(\mu) P_{\ell'}^m(\mu) d\mu = \frac{2\delta_{\ell,\ell'}}{2\ell + 1} \frac{(\ell + m)!}{(\ell - m)!}. \quad (\text{B.9})$$

It was shown in Section 1.2.2 that the a plane wave can be written as a linear combination of the VSH with only $m = 1$, which lead to the definition of the angular functions π_ℓ and τ_ℓ given by

$$\pi_\ell(\cos \theta) = \frac{P_\ell^1(\cos \theta)}{\sin \theta}, \quad \text{and} \quad \tau_\ell(\cos \theta) = \frac{dP_\ell^1(\cos \theta)}{d\theta},$$

which can be calculated recursively with Eq. (B.8) and the recurrence relations of the Legendre polynomials

$$(2\ell - 1)\mu P_{\ell-1}(\mu) = (\ell - 1)P_\ell(\mu) + \ell P_{\ell-2}(\mu), \quad (\text{B.10})$$

$$(1 - \mu)^2 \frac{dP_\ell(\mu)}{d\mu} = \ell P_{\ell-1}(\mu) - \ell \mu P_\ell(\mu). \quad (\text{B.11})$$

leading to

$$\pi_\ell(\mu) = \frac{2\ell - 1}{\ell - 1} \mu \pi_{\ell-1}(\mu) - \frac{\ell}{\ell - 1} \pi_{\ell-2}, \quad (\text{B.12})$$

$$\tau_\ell(\mu) = \ell \mu \pi_\ell(\mu) - (\ell + 1) \pi_{\ell-2}(\mu). \quad (\text{B.13})$$

where $\pi_1(\mu) = 1$ according to Eq. (B.8) and where $\pi_0(\mu) = 0$ is defined. Another notable result from Eq. (B.8) is that the angular functions $\pi_\ell(\mu)$ and $\tau_\ell(\mu)$, when evaluated at $\theta = 0$ ($\mu = 1$), follows

$$\pi_\ell(\mu = 1) = \left. \frac{dP_\ell(\mu)}{d\mu} \right|_{\mu=1}, \quad (\text{B.14})$$

$$\tau_\ell(\mu = 1) = \left[\frac{dP_\ell^1(\mu)}{d\mu} + (1 - \mu^2)^{1/2} \frac{d^2P_\ell(\mu)}{d\mu^2} \right] \Big|_{\mu=1} = \left. \frac{dP_\ell(\mu)}{d\mu} \right|_{\mu=1}, \quad (\text{B.15})$$

which can be obtained from the Legendre equation by setting $m = 1$ and $\mu = 1$ in Eq. (1.19), leading to

$$\pi_\ell(\mu = 1) = \tau_\ell(\mu = 1) = \frac{\ell(\ell + 1)}{2} P_\ell(\mu = 1) = \frac{\ell(\ell + 1)}{2}, \quad (\text{B.16})$$

where the last equality arises from the chosen definition of the Legendre polynomial [Eq. (B.8)].

The angular functions π_ℓ and τ_ℓ are not orthogonal in general, nevertheless $\pi_\ell(\mu) \pm \tau_\ell(\mu)$ are. To prove the orthogonality of $\pi_\ell \pm \tau_\ell$ let us apply the Legendre equation [Eq. (1.17)] to P_ℓ^m and multiply it by $P_{\ell'}^m$; repeating this procedure inverting ℓ and ℓ' and adding both equations it is obtained that

$$\begin{aligned} & \frac{d}{d\theta} \left(\sin \theta P_{\ell'}^m(\mu) \frac{dP_\ell^m(\mu)}{d\theta} \right) + \frac{d}{d\theta} \left(\sin \theta P_\ell^m(\mu) \frac{dP_{\ell'}^m(\mu)}{d\theta} \right) + \\ & [\ell(\ell + 1) + \ell'(\ell' + 1)] P_{\ell'}^m(\mu) P_\ell^m(\mu) \sin \theta = 2 \left(\frac{m P_\ell^m(\mu)}{\sin \theta} \frac{m P_{\ell'}^m(\mu)}{\sin \theta} + \frac{dP_\ell^m(\mu)}{d\theta} \frac{dP_{\ell'}^m(\mu)}{d\theta} \right) \sin \theta, \end{aligned} \quad (\text{B.17})$$

where it was added $2 dP_\ell^m/d\theta dP_{\ell'}^m/d\theta$ on both sides to complete the derivatives. Integrating Eq. (B.17) in the interval $\theta \in (0, \pi)$, or $\mu \in (-1, 1)$, and employing Eqs. (B.8) and (B.9), one obtains that

$$\int_{-1}^1 \left(\frac{m P_\ell^m(\mu)}{\sin \theta} \frac{m P_{\ell'}^m(\mu)}{\sin \theta} + \frac{dP_\ell^m(\mu)}{d\theta} \frac{dP_{\ell'}^m(\mu)}{d\theta} \right) d\mu = \delta_{\ell, \ell'} \frac{2\ell(\ell + 1)}{2\ell + 1} \frac{(\ell + m)!}{(\ell - m)!}. \quad (\text{B.18})$$

Additionally

$$\int_{-1}^1 \frac{m P_\ell^m(\mu)}{\sin \theta} \frac{dP_{\ell'}^m(\mu)}{d\theta} d\mu = \int_0^\pi m P_\ell^m(\mu) \frac{dP_{\ell'}^m(\mu)}{d\theta} d\theta = - \int_{-1}^1 \frac{m P_{\ell'}^m(\mu)}{\sin \theta} \frac{dP_\ell^m(\mu)}{d\theta} d\mu. \quad (\text{B.19})$$

where Eq. (B.8) was employed along integration by parts. Thus, combining Eqs. (B.18) and (B.19), it leads to

$$\int_{-1}^1 \left(\frac{m P_\ell^m(\mu)}{\sin \theta} \pm \frac{dP_\ell^m(\mu)}{d\theta} \right) \left(\frac{m P_{\ell'}^m(\mu)}{\sin \theta} \pm \frac{dP_{\ell'}^m(\mu)}{d\theta} \right) d\mu = \delta_{\ell, \ell'} \frac{2\ell(\ell + 1)}{2\ell + 1} \frac{(\ell + m)!}{(\ell - m)!}. \quad (\text{B.20})$$

The Eq. (B.20) is the orthogonality of $\pi_\ell(\mu) \pm \tau_\ell(\mu)$ when $m = 1$, which also simplifies the right hand side to $\delta_{\ell,\ell'} 2\ell^2(l+1)^2/(2\ell+1)$.

Vector Spherical Harmonics Orthogonality Relations

The VSH follow orthogonality relations inherited from the orthogonality of sine, cosine and the associated Legendre functions. Let us define the inner product as the integral in the solid angle between two vector functions as

$$\langle \mathbf{A}, \mathbf{A}' \rangle_\Omega = \int_0^{2\pi} \int_0^\pi \mathbf{A} \cdot \mathbf{A}' \sin \theta d\theta d\varphi. \quad (\text{B.21})$$

Under this inner product, all even VSH are orthogonal to the odd VSH, as well as all VSH with $m \neq m'$, due to the orthogonality of $\sin(m\varphi)$ and $\cos(m'\varphi)$. The remaining orthogonality relations can be obtained by employing Eq. (B.18), leading to

$$\begin{aligned} \langle \mathbf{L}_{em'\ell}, \mathbf{L}_{em'\ell'} \rangle_\Omega &= \langle \mathbf{L}_{om\ell}, \mathbf{L}_{om\ell'} \rangle_\Omega \\ &= \delta_{m,m'} \delta_{\ell,\ell'} (1 \pm \delta_{m,0}) \frac{2\pi}{2\ell+1} \frac{(\ell+m)!}{(\ell-m)!} \left[\left(k \frac{dz_\ell(kr)}{d(kr)} \right)^2 + \ell(\ell+1) \left(k \frac{z_\ell(kr)}{kr} \right)^2 \right], \end{aligned} \quad (\text{B.22})$$

$$\begin{aligned} \langle \mathbf{M}_{em\ell}, \mathbf{M}_{em\ell'} \rangle_\Omega &= \langle \mathbf{M}_{om\ell}, \mathbf{M}_{om\ell'} \rangle_\Omega \\ &= \delta_{m,m'} \delta_{\ell,\ell'} (1 \pm \delta_{m,0}) \pi \frac{2\ell(\ell+1)}{2\ell+1} \frac{(\ell+m)!}{(\ell-m)!} z_\ell^2(kr), \end{aligned} \quad (\text{B.23})$$

$$\begin{aligned} \langle \mathbf{N}_{em\ell}, \mathbf{N}_{em\ell'} \rangle_\Omega &= \langle \mathbf{N}_{om\ell}, \mathbf{N}_{om\ell'} \rangle_\Omega \\ &= \delta_{m,m'} \delta_{\ell,\ell'} (1 \pm \delta_{m,0}) \pi \frac{2\ell(\ell+1)}{2\ell+1} \frac{(\ell+m)!}{(\ell-m)!} \left[\left(\frac{z_\ell}{kr} \right)^2 + \left(\frac{1}{kr} \frac{d[krz_\ell(kr)]}{d(kr)} \right)^2 \right]. \end{aligned} \quad (\text{B.24})$$

$$\begin{aligned} \langle \mathbf{L}_{em\ell}, \mathbf{N}_{em\ell'} \rangle_\Omega &= \langle \mathbf{L}_{om\ell}, \mathbf{N}_{om\ell'} \rangle_\Omega \\ &= \delta_{m,m'} \delta_{\ell,\ell'} (1 \pm \delta_{m,0}) \pi \frac{2\ell(\ell+1)}{2\ell+1} \frac{(\ell+m)!}{(\ell-m)!} \left[\frac{z_\ell}{kr} \frac{dz_\ell(kr)}{d(kr)} + \left(\frac{1}{kr} \frac{d[krz_\ell(kr)]}{d(kr)} \right)^2 \right] \end{aligned} \quad (\text{B.25})$$

where $(1 + \delta_{m,0})$ is for odd VSH and $(1 - \delta_{m,0})$ for even VSH. The orthogonality relations of the VSH can be further simplify by means of the recurrence relations of the spherical Bessel/Hankel functions [Eqs. (B.3) and (B.4)], which imply that

$$\left[\left(k \frac{dz_\ell(kr)}{d(kr)} \right)^2 + \ell(\ell+1) \left(k \frac{z_\ell(kr)}{kr} \right)^2 \right] = k^2 [\ell z_{\ell-1}^2(kr) + \ell(\ell+1) z_{\ell+1}^2(kr)], \quad (\text{B.26})$$

$$\left[\left(\frac{z_\ell}{kr} \right)^2 + \left(\frac{1}{kr} \frac{d[krz_\ell(kr)]}{d(kr)} \right)^2 \right] = \ell(\ell+1) [(\ell+1) z_{\ell-1}^2(kr) + \ell z_{\ell+1}^2(kr)], \quad (\text{B.27})$$

$$\left[\frac{z_\ell}{kr} \frac{dz_\ell(kr)}{d(kr)} + \left(\frac{1}{kr} \frac{d[krz_\ell(kr)]}{d(kr)} \right)^2 \right] = \ell(\ell+1) [z_{\ell-1}^2(kr) - z_{\ell+1}^2(kr)]. \quad (\text{B.28})$$

Mie Theory Code

```

In[1]:= (*Angular functions pi and tau - n-> order - th -> polar angle theta*)
MiePi[n_, th_] := Module[{pi},
  pi[0] = 0; pi[1] = 1;
  pi[i_] := pi[i] = ((2i-1)/(i-1)) * Cos[th] * pi[i-1] - (i/(i-1)) * pi[i-2];
  pi[n]]

MieTau[n_, th_] := Module[{pi},
  pi[0] = 0; pi[1] = 1;
  pi[i_] := pi[i] = ((2i-1)/(i-1)) * Cos[th] * pi[i-1] - (i/(i-1)) * pi[i-2];
  n * Cos[th] * pi[n] - (n+1) * pi[n-1]]

SetAttributes[MiePi, Listable]
SetAttributes[MieTau, Listable]

In[2]:= MieCoefficient[n_, x_, m_] :=
Module[{an, bn, psiMX, dpsiMX, psix, dpsiX, xiX, dxix},
  If[! Apply[Equal, Length /@ {x, m, 0}],
    Return[Message[MieCoefficient::list, x, m]]];

{psiMX, dpsiMX} =
{m*x#, -n# + m*x*SphericalBesselJ[n-1, m*x]} & SphericalBesselJ[n, m*x];
{psiX, dpsiX} =
{x#, -n# + x*SphericalBesselJ[n - 1, x]} & SphericalBesselJ[n, x];
{xiX, dxix} = {psiX, dpsiX} +
I*x#, -n# + x*SphericalBesselY[n-1, x]} & SphericalBesselY[n, x];

an = (m*psiMX*dpsiX - psiX*dpsiMX)/(m*psiMX*dxix - xiX*dpsiMX);
bn = (psiMX*dpsiX - m*psiX*dpsiMX)/(psiMX*dxix - m*xiX*dpsiMX);

{an, bn}]

```



```

In[3]:= MieScatteringAmplitude12[x_, m_, angle_] :=
Module[{ab, poles, pitau, coeff, s1, s2},

(*Wacombe criteria for convergence*)
poles = Range[ Ceiling[ x + 4.*x^(1./3) + 2.]];

ab = MieCoefficient[poles, x, m];
pitau = Through[{MiePi, MieTau}[poles, angle]];
coeff = ((2.*# + 1.)/((# + 1.)*#)) & /@ poles;

s1 = Plus @@ (coeff * Plus @@ (ab*pitau));
s2 = Plus @@ (coeff * Plus @@ (ab* Reverse[pitau]));

{s1, s2}]

```



```

In[4]:= MieScatteringQ[indices_, wlength_, radius_] :=
Module[{ab, sum, x, poles},
  x = (2.*Pi*radius)*indices[[1]]/wlength; (*Size parameter*)
  (*Wacombe criteria for convergence*)
  poles = Range[ Ceiling[ x + 4.*x^(1./3) + 2.]];

  ab = Plus @@ ( Chop[#*Conjugate[#]] & @

```

```

MieCoefficient[poles, x, Divide @@ Reverse[indices]]];
sum = Plus @@ ((2.*# + 1 & /@ poles) * ab);
sum *= 2./(x^2)

In[5]:= MieExtinctionQ[indices_, wlength_, radius_] :=
Module[{ab, sum, x, poles},
x = (2.*Pi*radius)*indices[[1]]/wlength; (*Size parameter*)
(*Wacombe criteria for convergence*)
poles = Range[ Ceiling[x + 4.*x^(1./3) + 2.]];

ab = Plus @@ (Re[MieCoefficient[poles, x, Divide @@ Reverse[indices]]]);
sum = Plus @@ ((2.*# + 1 & /@ poles) * ab);
sum *= 2./(x^2)

In[6]:= MieAbsorptionQ[indices_, wlength_, radius_] :=
Module[{ab, sum, x, poles},
x = (2.*Pi*radius)*indices[[1]]/wlength; (*Size parameter*)
(*Wacombe criteria for convergence*)
poles = Range[ Ceiling[x + 4.*x^(1./3) + 2.]];

ab = Plus @@ ( (Re[#] - Chop[#!Conjugate[#]]) &@
MieCoefficient[poles, x, Divide @@ Reverse[indices]]);
sum = Plus @@ ((2.*# + 1 & /@ poles) * ab);
sum *= 2./(x^2)

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