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Classical and Semi-Classical Interaction of Matter with the Electromagnetic Field Project 2011

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Summary: The project addresses the motion of the matter polarization within the classical and semi-classical theories of matter interacting with the electromagnetic field. The main emphasis is put on the development of the original Electromagnetic Theory in Matter formulated recently by the author and coworkers[1] for finite-size bodies with particular geometries, near-field and sub-wavelength regime, surface and magnetic-field effects, oscillations of the depolarizing field, generalized Rabi oscillations, spin and nuclear quadrupole motion. The semi-classical formulation envisages the calculation of the level shift and natural width of the spectral lines, the role of the vacuum fluctuations, the dynamics of the reaction fields and even the merits and limits of the "stochastic electrodynamics". The project hopes to get an advanced knowledge in basic things like the role of the quantum fluctuations, the inherent statistical nature of the basic processes and, generally, to the limits of validity of the semi-classical approaches. Specific computations of fields, polarizations, forces and resonances will be carried out in this context, with relevance for new, promising areas of research as nanoplasmonics, metamaterials, metamolecules or terahertz radiation.

Scientific context and motivation. There is much interest nowadays in nanoplasmonics, metamolecules and metamaterials. The well-known ponderomotive forces or forces arising from electromagnetic fluctuations (van der Waals-London, Casimir forces) are relevant for a wide range of applications from surface and plasma physics[2] to molecular liquids[3] to geodynamic and auroral plasmas[4]. The momentum transfer between light and matter is currently exploited in atom cooling[5] and optical tweezers.[6] On the other side, light confinement in nanostructures is well known[7] as well as localized dipolar excitations in nanostructured surfaces.[8] Strong electric forces have been reported to act upon a small, neutral particle in a waveguide, as a consequence of the induced polarization.[9] Multiple plasmonic excitations can generate attractive forces between nanoparticles.[10] Forces generated by the plasmonic radiation have also been reported.[11]

All these very interesting results are new and very promising. Photonic circuits are envisaged, which concentrate and channel light, single adsorbed atoms are currently identified by surface enhanced Raman spectroscopy, special diffraction effects are pursued, as produced by corrugated surfaces. "A revolution in optical manipulation" seems to be expected,[12] with many unknown implications. On the other side the terahertz spectroscopy, radars and sensors are making progress.[13] As it is well known, this is a field of the purely classical, general physics, specifically electromagnetism. Such techniques are able to image targets with an amazing $\lambda/100$ resolution. In this context also, super-dense optical inscription in solid-state materials implies apparently a subwavelength electromagnetic regime.

The open problems in all these research areas consist in the lack of advanced knowledge of the origin, magnitude and full characterization of the electromagnetic fields generated by matter and their effects on matter. In all these problems a convenient description is missing of the behaviour of the electromagnetic phenomena in the sub-wavelength regime (or near-field regime). The new aspects this line of research can bring are related fundamentally to matter polarization, semi-classical treatment of matter interacting with radiation and coherent behaviour of the electromagnetic field interacting with matter. The author of the present project believes that such problems can be treated, with interesting results, by resorting to a detailed description of matter polarization, for finite-size polarizable bodies with specific geometries, in the context of classical and semi-classical electromagnetism, where coherence can be relevant. The new, main concepts the project suggests for these problems are therefore the dynamics of the matter polarization, including finite-size and surface effects, semi-classical approaches and coherence. On the other hand, such an approach may shed a certain light upon other interesting, more fundamental, questions, as the electromagnetic bakward reaction of the electromagnetic field upon charges and currents, the spontaneous emission, level shifts and natural width of the spectral lines, vacuum polarization and fluctuations, ultimately the relation between classical physics and quantum mechanics and quantum electromagnetic field. In a sense, the present project attempts to renew connection, in the new, modern context, with classical landmark investigations of the superradiance,[14] semi-classical spontaneous emission[15] or classical vacuum-fluctuations effects.[16]

Apart from the wide, topical interest, the motivation for the present project stems from the recent research of the author and coworkers on related poblems. For instance, a new method has been introduced for treating the propagation of the electromagnetic field in matter, based on the integral Kirchhoff solutions of Maxwell equations and various models of matter polarization.[1] The method led to the full description of the surface plasmons and polaritons in a half-space, a slab, a cylinder[17, 18] or a sphere,[19] as well as to a new derivation of the Casimir and van der Waals forces.[20] In a slightly different context, this research led us to formulate the concept of pulsed polariton accelerated by laser beams, with a complete characterization of its energy and transported charge. Advantage has been taken of the existence of the accelerated pulsed polariton to get coherent X- or gamma rays by Compton (Thomson) backscatering, leading thus to the proposal of a new concept of gamma ray laser.[21] On the other hand, the exact solution of the quasi-classical (coherent) interaction of the electromagnetic field with polarizable two-level matter led us to clarify long-standing imperfections in the classical (semi-classical) theory of the laser, and to give arguments against the usual nuclear concept of the gamma laser.[22] Based on the same technique, suitably extended and adapted, the electron-positron pairs created from vacuum has been given a new, for the first time complete, solution.[23]

Objectives. The project's objectives are: 1) refine and generalize as much as possible the original Electromagnetic Theory in Matter formulated by the author and coworkers;[1] 2) investigation of the semi-classical and coherence aspects of the radiation interacting with matter; 3) quantum-semiclassical relation, assessment of limits.

The importance of objective #1 consists in the practical strength any good, complete and powerful theory gives. "Nothing is more practical than a good theory" (Lenin). Making use of such a general and powerful approach we can treat many particular problems concerning, first, the matter polarization for finite-size bodies with particular geometries. Based on this methodology we can compute the electromagnetic fields, especialy in the subwavelength regime we are more interested in, their effects on matter, and hope to give a more complete characterization of these effects. In particular, we are interested in generalizing momenta oscillations which exhibit "Rabi frequencies" to variable and non-uniform fields. It is true that such a generalization implies more sophisticated mathematical techniques (in particular coupled integral equations, in contrast with the usual techniques of differential equations in electromagnetism), but, once solved, we may then enjoy new, relevant and reliable results. The main point of this objective is polarization motion in various contexts, including near field, retardation, surface effects, the effect of the magnetic field, the motion of the depolarizing fields, spin and nuclear quadrupole motion.

The importance of objective #2 resides in evaluating the new semi-classical and coherence features brought into the theory of matter interacting with radiation. The aim here is to compute forces of electromagnetic origin acting in the subwavelength regime both on microscopic (mesoscopic) and macroscopic scale and compare them with experimental results reported in nanoplasmonics, metamolecules, nanostructures, or classical plasmas generated by laser beams (if possible, auroral plasma will not be left aside). We are particularly interested in their dependence on the distance, frequencies, temperature. The well known (often claimed) resonant character of such effects will be given a special attention. We hope to substantiate this way the "revolution in optical manipulation", including light storage. We believe that the surface plasmon-polariton modes are of prime importance in such effects, and will focus our research at this stage on this, little known, feature of the electromagnetic fields in matter (see, e.g., Ref. [18]).

Objective #3 addresses more fundamental questions, like spontaneous emission, level shift and natural width of the spectral lines, the role of the vacuum fluctuations and even the merits and limits of the "stochastic electrodynamics" (see, for instance, Ref. [24]). This objective is a natural consequence and follow-up of the previous two objectives of the project, as it aims at extending the semi-classical approach to the border of the quantum limit. We hope to get an advanced knowledge in basic things like the role of quantum fluctuations, the inherent statistical nature of the basic processes and, generally, to the limits of validity of the semi-classical approaches. Such a basic knowledge will give, on one hand, full reliability to the results and, on the other hand, will sugest new developments of the theoretical tools as well as experimental tests.

Method and approach. The objectives of the project will be approached by the specific research methodology of the theoretical physics. This implies a documentation phase, one or several working hypotheses, the testing of the hypotheses against the physical soundness of the problem and mathematical rigour, comparison with other known results, with experiments, etc. This work is usually carried out in discussions, seminars and individual computations, calculations. The project's team will probably consists of dr. LCC and dr. GV (scientific researchers 3rd class in the host Institute for Physics and Nuclear Engineering, Magurele-Bucharest), dr. MG (scientific researcher 1st class in the Institute for Lasers, Plasmas and Radiation, Magurele-Bucharest) and FDB (former scientific researcher 1st class in the host Institute for Physics andd Nuclear Engineering, Magurele-Bucharest), all former or current collaborators of the project's director.

The working plan includes the following milestones: 1) the project's first year will be devoted to the generalization of the original Electromagnetic Theory in Matter to polarization fields in various geometries (as described in the **Objectives** above), in order to assess the possible various effects of the electromagnetic fields acting upon material bodies (objective #1). Special attention will be given at this stage to the surface plasmon-polaritons. The main task will be carried out by the project's director, aided by the first two participants (LCC, GV). The generalized Rabi frequencies will be treated mainly by the project's director. MG and FDB will take part in assessing the physical consistency of the theoretical results especially in comparison with experiments; 2) the second year of the project will be devoted to specific computation of forces in the subwavelength regime. Special attention will be given to the new aspects the semi-classical treatments and the coherence may bring upon such phenomena (objective #2). The specific tasks will be carried out in the same formula as for the milestone #1. A particular test of the approach will be given at this stage by reformulating the equation of motion for the nuclear magnetic resonance (as well as for the nuclear quadrupole resonance), where an increasing need is felt for a rigorous evaluation of the limits of the semi-classical approach. This task will be carried out by the project's director; 3) the third year of the project will be devoted to investigating fundamental aspects of the semi-classical approaches (objective #3). Concomitantly, new aspects of the research carried out in the previous two years of the project may appear, unknown at the moment of writing up the project; they will be tackled in the third year of the project. This stage is also devoted to the synthesis of the results. The main task here will be carried out by the project's director. The project's director will be commited 36 man-months, LCC and GV will be assigned 24 man-months each, and MG and FDB only 18 man-months each. Now and then, electronic calculations or data manipulation may be needed, so the project assumes 4 (four) PCs/laptops (they will be needed starting with the second year of the project). Some other details of the specific problems to be investigated, or particular techniques to be used, cannot be fully given at this moment, before publication of the results. It is our plan that each milestone will end up with at least one publication. Participation to casual conferences, seminars, workshops, etc will be done, in order to diseminate the results in a high-quality manner. One or two doctoral or post-doctoral positions may be available in the course of the project.

Impact, relevance, applications. We will try to publish our results in most visible scientific journals, according to their scientific merits. We will diseminate the results by public seminars. The project's director and MG have delivered along the whole year 2010 6 (six) General Seminars on the campus Magurele (I. Electron pulses accelerated by polaritonic laser beams, III. Gamma lasers controlled by high-intensity external fileds, VI. Electron-positron pairs created from vacuum by external fields), under the generic title "Pulse and Impulse of ELI", concerning the electron accelerated by focused laser beams, their interaction with matter, the related gamma ray laser and vacuum polarization. All these Seminars were original, and their contents have been published in 2010-2011 in 5 papers in international high-ranked ISI journals. One of those papers (M. Apostol and M. Ganciu, J. Appl. Phys. 109 013307 (2011), Ref. [21]) has been highlighted by the journal's editors (see additional material). It is presumable that this series of Seminars have had an impact on the scientific communiy. We envisage a similar impact of the results of the present project. The project brings a new approach to the polarizable matter interacting with the electromagnetic field, both at the conceptual and technical levels, amenable to specific computations. The results of these calculations are relevant both for the "hot" field of nowadays plasmonics and optical manipulation and the range of radio or terahertz frequencies. While we expect a distinctive impact of our results to the former field of research, the latter field may enjoy new, valuable applications. However, the most valuable gain of the Project is probably the definite increase of qualification and competencies of the project's team in a new, promising area of research.

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