Atom "Meta-Optics": Negative-Index Media for Matter Waves in the nm wavelength range

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Abstract: Meta-optics is extended to matter waves. "Co-moving" magnetic fields in Stern-Gerlach interferometers allows producing negative group velocity of atomic wave packets, resulting into a negative refraction of the matter wave and atom "meta-lenses".

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With the fast development of matter-wave optics, many of the functions previously operated in light optics have been realised: atom diffraction, atom mirrors, beam splitters, atom interferometry, atom holography, quantum reflection of atoms, quantum atom statistics, etc. Similarities and differences originate in the properties of the associated particle: non-zero atom mass, vacuum dispersion for the "*de Broglie*" waves (implying the wave packet spreading), scalar character of the atomic wave function, influence of the internal atomic degrees of freedom… Along this viewpoint, novel areas in the field of atom optics are presently explored. For instance, it includes atom interferometry at the nanoscale: an "atomic nanoscope" [1], based on a Fresnel-type biprism atom interferometer, is presently in progress and an analysis of the influence of gravity on this type of atom interferometer has been performed [2].

Here we would like to show that the control of atomic motion by use of specific magnetic field configurations acting on the internal state of the atoms, allows one to devise original operations in matter wave optics. Magnetic field gradients are important: they are used to implement magnetic traps, a key step on the way to Bose Einstein condensation. Along those lines, we recently proposed a specially designed transverse Stern-Gerlach interferometer (two magnetic quadrupoles in series) [3]. This interferometer spatially modulates the transverse phase of an atomic beam in such a way that non-diffracting atom nano-beams should be generated at the exit. The non-diffracting character is linked to the special shape of the resulting transverse profile which is of the Lorentz type. The transverse intensity variations are smoother than those in a Gaussian beam and result in a far-field diffraction pattern narrower by several orders of magnitudes than ordinary Gaussian beams or atom beams diaphragmed by a nano-aperture. Those beams can be compared with Bessel beams in light optics [4] and have potential applications in atomic lithography and deposition or as a nano-probe of surfaces.

The extension of so-called "left-handed" optical meta-materials to negative-index media for matter waves is a topic of particular importance [5]. Since the seminal paper of V.G. Veselago [6] about "left-handed" media for light optics, a number of works have been devoted to these new media, their properties and their applications (negative refraction, perfect focussing, reversed Doppler Effect, cloaking, etc.) in various spectral domains. Such media are essentially characterised by a negative value of the optical index, which results into opposite directions of the wave vector k and the Poynting vector R. Their counterpart in atom optics is far from being obvious because atoms at mean - and *a fortiori* low - velocity (a few hundreds of m/s down to a few m/s or less) cannot penetrate dense matter. An alternate way to act on atomic waves *in vacuo* is to use an interaction potential due to some external field. Indeed when a semi-classical description of the external atomic motion is justified, an inhomogeneous static potential V(r) is equivalent to a refraction index n(r). This comes from the fact that the optical path accumulated along a ray *C* (*i.e.* a classical trajectory) is given by the path integral $\int_C K(r)\,ds$, where $K(r) = k\,[1 - V(r)/E_0]^{1/2}$ is the local wave number, k and E_0 being respectively the wave number and the kinetic energy of the atom in absence of potential, s is the curvilinear abscissa along the ray. This naturally leads us to set an atomic index $n(r) = [1 - V(r)/E_0]^{1/2}$. Nevertheless such a type of potential cannot be a solution for our purpose because the index n is either real and positive in classically allowed regions, or purely imaginary in classically forbidden regions, but it is nowhere real negative. This looks like an *impasse*. Our approach relies on both position- and time-dependent magnetic potentials to devise an atomic "meta-lens" [5]. We have shown that a novel class of recently introduced potentials - "*comoving" magnetic potentials*, which co-propagate with the atom wave [7] - provides us with a remarkably simple solution to devise negative-index media for matter waves [5]. In this way, a calculation of the matter-wave phase-shift demonstrates the possibility of producing transient negative group velocities for the atomic wave packet. With an appropriate time-dependence of the co-moving field, it allows us to devise cylindrical or spherical “meta-lenses” able to re-focus the atom wave (Fig.1). This represents an extension of “meta-optics” down to the nanometre wavelength range. Among the amazing properties of such materials (negative refraction, perfect focussing, cloaking, etc.), one is the enhancement (instead of attenuation) of evanescent matter waves. This and other properties of negative-index media for atom optics will be discussed.

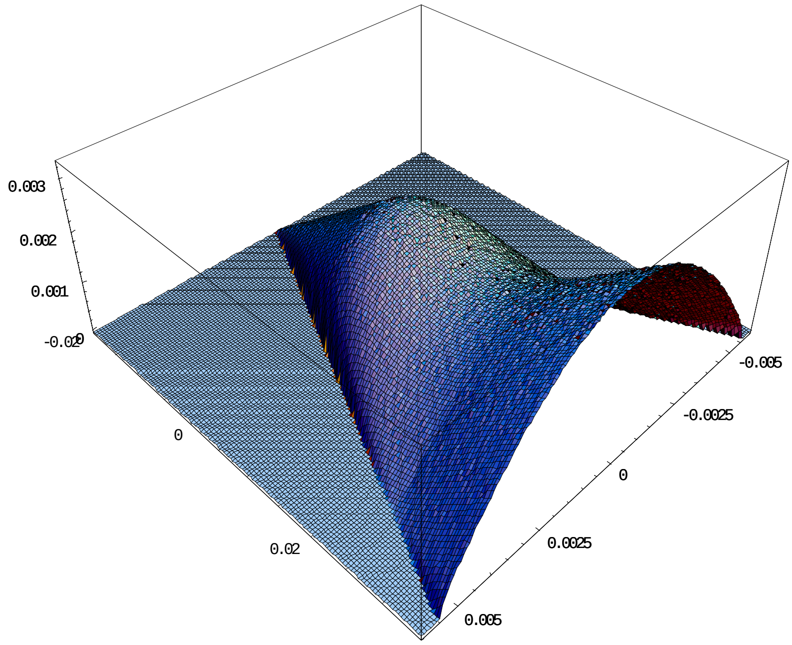

Fig.1. 3D representation of half a cone of atomic rays issued from a point-like source and making an angle 0.1 rad with the z axis. All rays exhibit a negative refraction and finally emerge parallel to their initial direction (from ref. [5]). The simulation is done for Ar atoms at velocity 20m/s, i.e. λ = 0.56 nm [5].

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