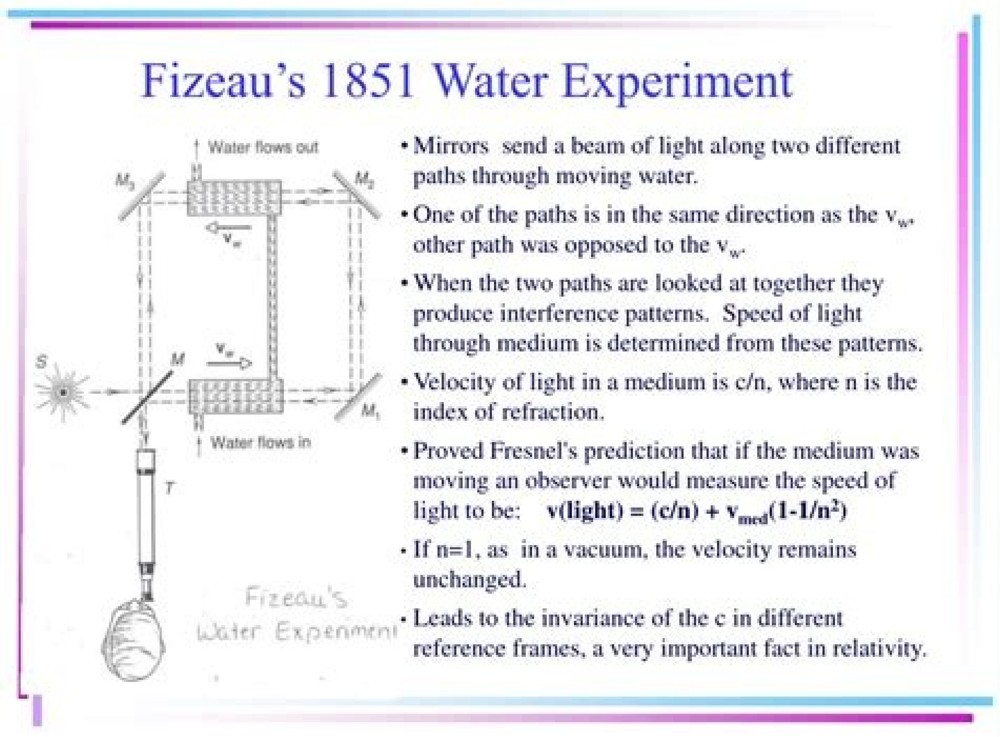
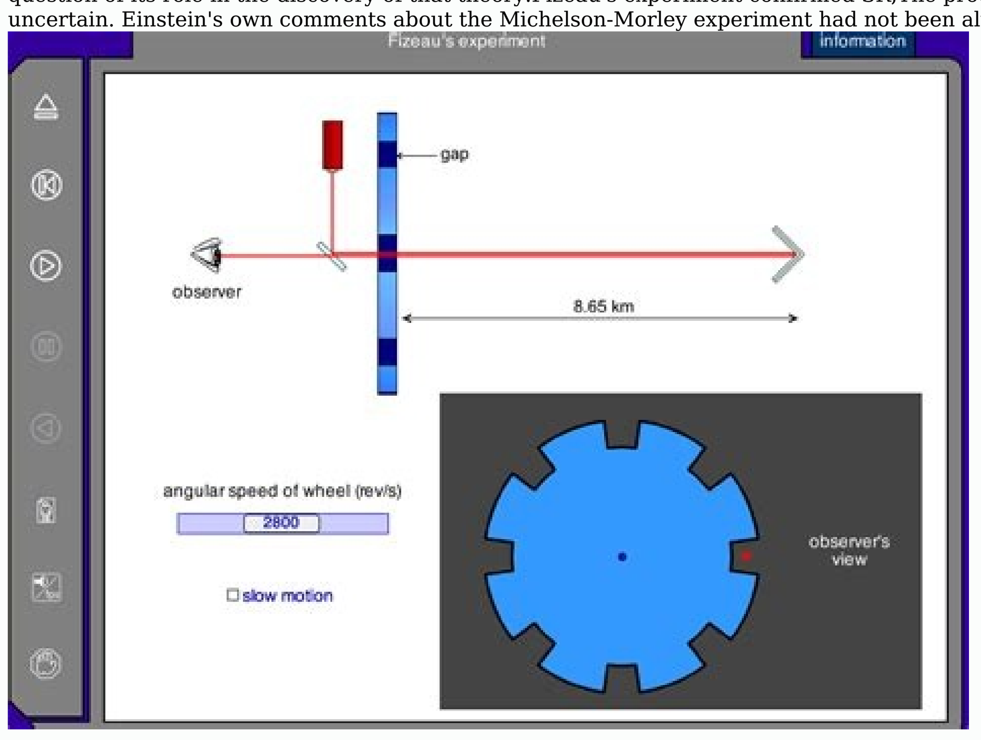
Fizeau experiment pdf

Download PDF Abstract: In 1895 Hendrik Antoon Lorentz derived the Fresnel dragging coefficient in his theory of immobile ether and electrons. This derivation did not explicitly involve electromagnetic theory at all. According to the 1922 Kyoto lecture notes, before 1905 Einstein tried to discuss Fizeau's experiment "as originally discussed by Lorentz" (in 1895). At this time he was still under the impression that the ordinary Newtonian law of addition of velocities was unproblematic. In 1907 Max Laue showed that the Fresnel dragging coefficient would follow from a straightforward application of the relativistic addition theorem of velocities. This derivation is mathematically equivalent to Lorentz's derivation of 1895. From 1907 onwards Einstein adopted Laue's derivation. When Robert Shankland asked Einstein how he had learned of the Michelson-Morley experiment, Einstein told him that he had become aware of it through the writings of Lorentz, but only after 1905 had it come to his attention.

"Otherwise", he said, "I would have mentioned it in my paper". He continued to say that the experimental results which had influenced him most were stellar aberration and Fizeau's water tube experiment. "They were enough". Indeed the famous Michelson-Morley experiment is not mentioned in the 1905 relativity paper; but curiously Einstein did not mention Fizeau's experimental result either, and this is puzzling in light of the importance of the experiment in Einstein's pathway to his theory. In this paper I try to discuss this question. From: Gali Weinstein Dr [view email] [v1] Mon, 16 Apr 2012 07:51:53 UTC (718 KB) Access through your institutionVolume 65, February 2019, Pages 55-72 rights and contentThe process of discovery of scientific theories is in general difficult to establish.
Published works, especially articles in professional journals, do not reveal very much about the process of trial and error that preceded the final formulation of a theory or the settlement of a fundamental equation. The sources that are relevant to the context of discovery include autobiographical books or notes, letters, and unpublished manuscripts but, sometimes, these sources are sparse and not necessarily enlightening. The discovery of the special theory of relativity (SR) in Einstein's thought –a topic on which thousands of pages have been written- is a vivid example of this situation. Einstein did not publish anything on the electrodynamics of moving bodies before 1905. His 1905 paper on SR presented this theory as based on two fundamental hypotheses taken as postulates-the relativity principle and the light principle-without any references to his predecessors.1 In later works, Einstein did not offer many details about his background knowledge concerning the work of Michelson and Morley and other previous experiments related to the optics of moving bodies.2 Einstein's (1949) short autobiography provides many historical details, but it does not mention precise dates, places or names; in particular, Fizeau's (1851) experiment and the Michelson and Morley (1887) experiment are not mentioned. These facts have posed well-known conundrums to every historian of science, which we do not intend to address here.3 By contrast, the genesis of the general theory of relativity is much better documented and has been extensively scrutinized by many scholars in recent years.4In 1925 Einstein gave a lecture series at the University of Buenos Aires; he started his first lecture on 25 March 1925 by saying that Fizeau's 1851 water tube experiment was "perhaps the most fundamental to the theory of special relativity" (Einstein, 1925, pp. 915–916; trans., p. 941). However, he did not explain why it was so important. Experiments frequently play a specific role both in the context of discovery and in the context of justification of scientific theories, and this seems to be the case of Fizeau's experiment. As we shall see, Fizeau's experimental result was conceived as providing confirmatory evidence for SR, but this happened after 1907 when it was discovered that SR entailed a first-order approximation to this result and was able to offer a simple explanation of it. On the other hand, Einstein often claimed that Fizeau's experiment was decisive in his path to the theory before 1905, and he repeated this remark even until 1950 (see section 2 for detailed quotations). However, given that by 1905 he did not know that his theory explained Fizeau's experiment as a case of relativistic velocity addition, the question is: which was the relevance of that experiment in his search for a new theory?In order to pave the way for answering this question, we have surveyed all the available sources in which Einstein referred to Fizeau's experiment. We found that since 1907, with three noticeable exceptions –not written by Einstein himself-, he regarded that experiment as confirmatory for his theory, even as a crucial experiment in its favor.5 Following those sources , we intend to establish the precise role played by Fizeau's experiment in the context of justification of SR. We will determine what it precisely confirmed and with respect to which theories it was crucial theories it was crucial, either for or against. Finally, we will address the issue of the relevance of this experiment in Einstein's process of discovery.Our principal aim is to make a revision of all the available evidence in Einstein's works in order to show how the meaning of Fizeau's experiment was reinterpreted within a new conceptual framework which made possible for it to be conceived as a crucial experiment in favor of SR, while in its own time it was considered as crucial for a particular hypothesis concerning the interaction between ether and matter.The structure of the article is the following.



In section 2 we review the available evidence in Einstein's works on the role played by Fizeau's experiment in the discovery of SR. In section 3 we make a detailed analysis of Fizeau's 1851 water tube experiment. In section 4 we show that the interpretation of Fizeau's experimental outcome was troublesome in its own time and that the explanation in terms of partial dragging of ether by matter was not acceptable for many physicists, including Fizeau himself. In section 5 we present the relativistic explanation of Fresnel's formula. In section 6 we discuss Einstein's reinterpretation of Fizeau's experiment as crucial in favor of the relativistic transformation of velocities and against the Galilean transformations. In section 7 we analyze the reasons why the experiment was taken as providing confirmatory evidence for SR. We also discuss the reasons Einstein's invoked to argue that his theory had to be preferred over the empirically equivalent alternative provided by Lorentz's electron theory. In section 8 we make two conjectures about the role played by Fizeau's experiment in the discovery of SR. We then conclude by pointing out that this experiment was reinterpreted within a new theoretical framework, in which the very concept of velocity has undergone a significant conceptual change.The role of Fizeau's experiment in the discovery of SR has been anything but clear. For many years it remained unnoticed to the majority of historians and philosophers of science, who only took into account the Michelson-Morley, 1887 experiment. Einstein did not mention this experiment in his original 1905 article. There is evidence –certainly not decisive-that Einstein was acquainted with this experimental result before he discovered his theory of relativity. But we also know that he did notAccording to the undulatory theory, light is capable of propagating inside transparent media, such as water or glass, because these media are permeated by luminiferous ether. Within this theoretical framework it is natural to ask whether the speed of light is affected by the motion of material media. In principle, it is possible to assume that matter is able to interact with the ether so that three different hypotheses could account for the phenomena. Either the luminiferous ether is completely The real explanation of Fizeau's experimental result was the subject of different interpretations from its very beginning. The last paragraph in his 1851 and 1859 publications we have quoted above shows that he was hesitant about the ultimate meaning of his own results. In particular, he had serious doubts about interpreting it as confirming Fresnel's hypothesis of partial convection of ether by matter. By contrast, Fizeau's articles did not express any doubts concerning the very existence ofEinstein did not mention Fizeau's experiment in his 1905 groundbreaking paper in which he formulates SR. Einstein discussed the optics of moving bodies in section 7 of his paper, where he derived the relativistic formulae for stellar aberration and the Doppler effect in a more general formulation. Significantly, he placed this treatment of optical phenomena within the electromagnetic part of the paper. According to his own words (Einstein, 1905, p. 911), he applied "the transformation equations Einstein's first systematic review article of SR was finished by the end of November 1907, just a few weeks after the publication of Laub's and Laue's articles. In the very beginning of that paper, Einstein (1907, p. 436) gave explicit credit to those physicists. He consequently modified his treatment of the optics of moving bodies that was now placed within the kinematical part of the paper, instead of the electrodynamic part, as it was in 1905. After formulating the relativistic additionAs we have seen, Einstein regarded Fizeau's experiment as crucial with respect to different rival theories. What has precisely this experiment confirmed and refuted? With respect to which particular theories or hypotheses was it crucial? In this section, we shall assess in the first place how Fizeau's experiment provided confirmatory evidence for SR, and in the next section, we proceed to consider the harder question of its role in the discovery of that theory.Fizeau's experiment confirmed SR,The process by which Einstein discovered SR probably cannot be reconstructed with certainty, as it occurs with many other outstanding scientific discoveries. The role played by the experimental results concerning the optics of moving bodies has been particularly uncertain. Einstein's own comments about the Michelson-Morley experiment had not been always coherent along his life.60We thank two anonymous reviewers of a previous version of this article for their detailed comments and criticisms.



We acknowledge Rafael Ferraro for his helpful discussions concerning the relativistic interpretation of Fizeau's experiment. We have benefited from grants by Consejo Nacional de Investigaciones Científicas y Técnicas of Argentina (PIP 586) and by Universidad de Buenos Aires (UBACyT 333BA, and UBACyT 343B).P. AcuñaM. Frisch et al.M. JanssenS. AbikoS.
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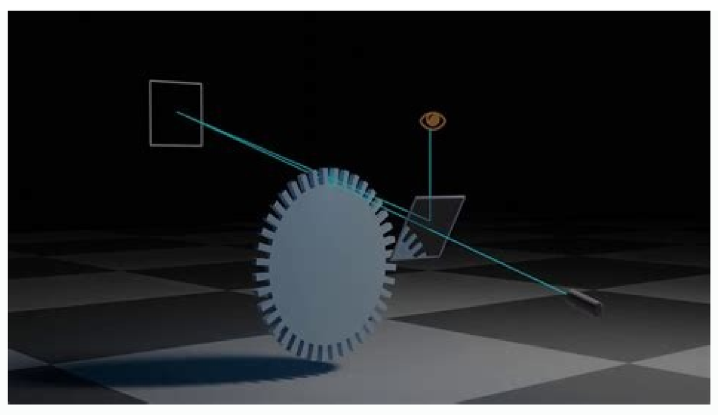

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EinsteinA. EinsteinJ. EisenstaedtG. FitzGeraldEnhancing the optical response and Fresnel–Fizeau light dragging in relation to photon plus surface plasmons through various coupled atomic–metal plasmonic interfaces has prompted great interest recently. This is due to the many potential implications of optical properties and drag of light, both from fundamental and technological viewpoints. Herein, we report theoretical results on the quantum-coherence enhanced optical features and light dragging through a well-shaped ensemble of quantum dot molecules (QDMs) and plasmonically coupled dot–(metal)nanoparticle interface. To investigate and tune the required optical properties and light dragging in the superluminal and subluminal regimes, we employed interdot tunneling-driven quantum coherence via electromagnetically-induced transparency (EIT) and plasmonically-induced transparency (PIT). Specifically, in order to determine the required theoretical results, we employed a density-matrix formulation to calculate the complex susceptibility of probe/signal pulse through the proposed QDM. We interpreted the light drag and optical response of probe field and surface plasmons via dressed eigenstates of PIT/EIT and Fano-type quantum interference in the proposed QDMs and dot–metal nanoparticle plasmonic interfaces. Unlike bulk metals, to account for the reduced electron mean free path, hereby, we employed the size-dependent corrected dielectric constant of the Drude model. The maximum predicted value of the wave vector for surface plasmons was 2m−1, which led to greatly enhanced propagation length of the order of 0.25 m. The calculated wavelength was 162.91×10−3 m, corresponding to a quality factor of 9.64.In this contribution we present ab initio results for ionization total cross sections, probabilities at zero impact parameter, and impact parameter moments of order +1 and −1 of Ne, Ar, Kr, and Xe by proton impact in an extended energy range from 100 keV up to 10 MeV. The calculations were performed by using the continuum distorted wave eikonal initial state approximation (CDW-EIS) for energies up to 1 MeV, and using the first Born approximation for larger energies. The convergence of the CDW-EIS to the first Born above 1 MeV is clear in the present results. Our inner-shell ionization cross sections are compared with the available experimental data and with the ECPSSR results. We also include in this contribution the values of the ionization probabilities at the origin, and the impact parameter dependence. These values have been employed in multiple ionization calculations showing very good description of the experimental data.
Tables of the ionization probabilities are presented, disaggregated for the different initial bound states, considering all the shells for Ne and Ar, the M-N shells of Kr and the N-O shells of Xe.A well-established nonlinear continuum model of time-independent electrodiffusion describes the migrational and diffusional transport of two ionic species, with equal and opposite valences, across a liquid junction. The ionic charge densities provide the source for a static electric field, which in turn feeds back on the charges to contribute the migrational component of the ionic transport. Underpinning the model is a form of the second Painlevé ordinary differential equation (PII). When Bäcklund transformations, extended from those known in the context of PII, are applied to an exact solution of the model first found by Planck, a sequence of exact solutions emerges.
These are characterized by corresponding ionic flux and current densities that are found to be quantized in a particularly simple way. It is argued here that this flux quantization reflects the underlying quantization of charge at the ionic level: the nonlinear continuum model 'remembers' its discrete roots, leading to this emergent phenomenon.In this letter, we discuss an expression of the continuous fractal entropy. The expression proposed fulfills in a rigorous way the dimensionless criterion and it is strictly positive overall space, the applications were done on the first thirty-six neutral atoms and in a set of 1863 molecules. The results obtained in molecules, permit us to introduce the concept of par-paene-entropic molecules, which means molecules with almost the same entropic content, this permits us to identify some groups of molecules that could be structurally different but some of them could be equivalent from the chemical reactivity point of view.By performing resummation of small fermion–antifermion pairs within the pentagon form factor program to scattering amplitudes in planar N=4 superYang–Mills theory, we construct multichannel conformal blocks within the flux-tube picture for N-sided NMHV polygons. This procedure is equivalent to summation of descendants of conformal primaries in the OPE framework. The resulting conformal partial waves are determined by multivariable hypergeometric series of Lauricella–Saran type.In his "'From the Phenomena of Motions to the Forces of Nature': Hypothesis or Deduction?" of 1990 Howard Stein reinvigorated a centuries-old dispute over whether Newton had derived his law of gravity from phenomena. More specifically, Stein – like such notables before him as Euler – challenged whether any phenomenon involving gravity served as a basis for Newton inferring that his third law of motion applies to gravity, and with it for inferring that the mass of the attracting body belongs in the numerator of the law. Stein ends up conjecturing that Newton's conception of forces of nature as forces of interaction "was actually developed by Newton at the same time that he was discovering the law of gravitation." This paper assesses this conjecture by examining the manuscripts – including deletions and insertions – that we have from 1685, the year during which the theory of gravity emerged and the Principia took shape. The conclusion is not merely that the manuscript evidence supports Stein's conjecture, but more significantly that the driving consideration behind both the Newtonian conception of forces of nature as forces of interaction and the inclusion of the mass of the attracting body in the numerator of the law was that the mass of the attracted body, as inferred from phenomena, must be included in the numerator – that is, the phenomena establishing that gravitational forces, unlike any other kind of forces, somehow "proportion themselves" to the individual bodies on which they act.View full text Large Fizeau's light-dragging effect in a moving electromagnetically induced transparent medium Your article has downloaded Tian Qin, Jianfan Yang, … Wenjie Wan N. G. C. Astrath, G. A. S. Flizikowski, … S. E. Bialkowski Nikita Kavokine, Shuangyang Zou, … Lydéric Bocquet Rico Gutzler, Manish Garg, … Klaus Kern Masato Ota, Koichi Kan, … Makoto Nakajima Y. Dong, L. Xiong, … D. N. Basov Tomaž Požar, Jernej Laloš, … Nelson G. C. Astrath M. E. Mossman, T. M. Bersano, … P. Engels Mikko Partanen, Hyeonwoo Lee & Kyunghwan Oh As one of the most influential experiments on the development of modern macroscopic theory from Newtonian mechanics to Einstein's special theory of relativity, the phenomenon of light dragging in a moving medium has been discussed and observed extensively in different types of systems. To have a significant dragging effect, the long duration of light travelling in the medium is preferred. Here we demonstrate a light-dragging experiment in an electromagnetically induced transparent cold atomic ensemble and enhance the dragging effect by at least three orders of magnitude compared with the previous experiments. With a large enhancement of the dragging effect, we realize an atom-based velocimeter that has a sensitivity two orders of magnitude higher than the velocity width of the atomic medium used. Such a demonstration could pave the way for motional sensing using the collective state of atoms in a room temperature vapour cell or solid state material.
The phase velocity of an electromagnetic wave travelling in a moving medium with velocity v deviates from the velocity of light in vacuum c.
Naively, one might expect that in the low speed limit v<A recent experiment shows the phase velocity dragging in a hot atomic vapour cell by shifting the frequency away from the resonance to avoid the absorption and improves the dragging coefficient Fd by two orders of magnitude7. There are proposed experiments using an electromagnetically induced transparent (EIT) medium to enhance the dragging effect for the study of motional sensing, transverse light dragging and laboratory analog of astronomical systems, such as event horizon in the black hole8,9,10,11,12,13. Group velocity dragging under EIT has been shown in a stationary hot vapour by selecting a group of atoms through optical pumping14.In the following, we demonstrate phase velocity dragging in a moving cold 85Rb atomic ensemble under EIT. An enhancement of the dragging coefficient is achieved by three orders of magnitude compared with the previous experiment7. Taking advantage of the large dispersion property of EIT medium, we also show the collective state of atoms can be applied for velocimetry in which the sensitivity is 100 times higher than the Doppler width of the ensemble used.Electromagnetically induced transparency has been studied substantially in both atomic vapours and solid system over the past two decades15. Owing to its extraordinary property of slowing down the group velocity of light in a medium without absorption, it finds applications in quantum optics and information science15,16,17. A simple EIT scheme can be implemented in a three-level atomic system, wherein two lower atomic states |g> and |s> with long coherence time are coupled to a third state |e> by optical excitations. A control field resonating on the |s> to |e> transition creates a quantum interference for a probe field resonating on the |g> to |e> transition such that the real and imaginary part of the susceptibility χ can both approach to zero at the resonance. The slope of the real part of the susceptibility determines the group velocity as can be seen from the index of refraction n≈1+(1/2)Re[χ] and the group velocity Vg=c/(n+ω(n(ω)/ω)). The magnitude of group velocity near the resonance can be approximated as Vg∝(ΓgeΓgs+Ωc2)/N, where N is the density of atoms, Γge is the decoherence rate of |g> and |e>, Γgs is the decoherence rate of |g> and |s>, and Ωc is Rabi frequency of the control field15. The group velocity of the probe field can, therefore, be reduced by lowering the control field intensity or increasing the atom density. Our three-level system involves 85Rb D2 line |g>≡|52S1/2, F=2>, |s>≡|52S1/2, F=3>, and |e>≡|52P3/2, F′=3> as shown in Fig. 1.
Figure 2 shows a typical EIT spectrum of our experiment. We fit the spectrum with the transmission T=exp(OD × (Γge/2) × Im[χ]) of the probe field15 and obtain OD=36, where OD=NL3λ2/2π is the optical depth of the ensemble, L is the length of the ensemble, and λ is the wavelength of the probe field. To change the velocity of the center-of-mass motion of the ensemble, we apply a resonant scattering force by imparting a push field on the ensemble.
The velocity change is then controlled by the power of the push field.Figure 1: Experimental details.(a) Level diagram of relevant atomic transitions for the experiment. (b) Experimental set-up: BS is a beam splitter. PBS is a polarizing beam splitter. AOM is an acoustic-optical modulator. We use a magnetic indexing mount to switch between pushing atoms upward and downward. In the pushing upward set-up, the push field is overlapped with the control field and coupled to a single mode fiber. In the push downward case, the push field is coupled backward to the control field fiber exiting port with 75% coupling efficiency to ensure the overlap of the control and push field. Detector 2 records the reference field for comparing the phase of the probe field from detector 1 on an oscilloscope.
The local gravity g is pointing downward. The probe field frequency is ωp. The probe and control fields are aligned around 183°. (c) Timing sequence of the experiment. Magneto-optical trap (MOT) represents the timing sequence for cooling and repumping fields as well as the magnetic field for the preparation of the cold atomic ensemble. The push field is on at t=t1 and t=t2 for the determination of the velocity by imaging the position of the atomic cloud 1 and 3 ms after the push field.Figure 2: Transmission of the probe field versus detuning.The probe field is on 52S1/2, F=2 to 52P3/2, F′=3 transition and the control field is on 52S1/2, F=3 to 52P3/2, F′=3 transition. The probe field detuning is expressed in terms of excited state spontaneous decay rate Γ. The standard error of each data point is calculated from the average of three experimental trials. (a) Electromagnetically induced transparency spectrum for optical depth (OD) measurement. The fitting curve shows OD=36.0(0.4) and control field Rabi frequency Ωc=0.582(5)Γ. The duration of the probe field is 100 μS and the control field is turned on 100 μS before the probe field is on in order to prepare the state of atoms in the 52S1/2, F=2.
The standard error of the central peak is calculated from five data points while the rest are two data points. (b) Transmission peak of probe field with 2 mW (black squares) and 0.6 mW (blue circles) control field power. The fitted Gaussian functions of black squares an blue circles give 1/e2 width of 0.306(6)Γ and 0.134(1)Γ, respectively. The standard error of each data point is calculated from the average of three experimental trials.MeasurementDefining the group index of the medium ng≡c/Vg when it is larger than one, the dragging coefficient can be rewritten as Fd=ng/n-1/n2. The index of refraction n of a medium near the EIT transmission window is approximately unity15, so the phase velocity can now be further simplified as vp=c+ngv. To detect the light-dragging effect, we compare the phase of the probe field with a local oscillator through the method of heterodyne detection18. Considering the phase shift of the probe field passing through a medium with a length L as Φ=kL, where k is the wavevector of the field and propagating along the direction of the moving medium, we can rewrite the phase with the definition of the magnitude of the phase velocity vp≡ω/k and obtainwhen v<3 with control field power of 2 and 0.6 mW.Figure 3: Phase and group delays of the probe field versus velocity of the atomic ensemble.(a) With control field power of 2 mW. The black solid squares are the measured phases and the black open squares are the expected phases (left axis) from equation 4 and group delay measurements. (b) With control power of 0.6 mW. The blue solid circles are the measured phases and the blue open circles are the expected phases (left axis) from equation 4 and group delay measurements. The red solid triangles are the group delay times (right axis). The phase delay are measured in terms of the delay time. One cycle corresponds to 1/70 MHz=14.29 ns. The measured phase uncertainty is by taking the standard error of three cycles of 70 MHz sinusoidal wave in the probe field envelope and averaging for 20 experimental cycles.
Each experimental cycle takes 2 s. The group delay of the probe field is measured at each velocity by fitting the center of the probe field pulse with a Gaussian function.To confirm the light-dragging effect, we calculate the expected phase shift using equation 4. The group delay of the probe field is measured at each velocity by fitting the center of the probe field pulse with a Gaussian function. The discrepancy between measured and calculated phase shift is mainly due to the effect of other hyperfine states in the EIT process and also the systematic error of velocity measurement due to the distortion of the atomic cloud after interacting with the pushing field. To take out the extra phase due to the EIT process, we fit our measured phases with a linear function and offset the fitting line to zero when the velocity is at zero. Figure 4 shows the measured delayed phases at the control field power of 0.6 and 2 mW and the expected phase delays are in a good agreement within one standard error. With the measured atomic cloud size 1.4 mm and our largest group delay time t=855 ns, the dragging coefficient Fd in our experiment has reached 1.83 × 105.Figure 4: Phase delay of the probe field with offset versus velocity of the atomic ensemble.The phase delay times from Fig. 3 are offset to zero at zero velocity.
The solid circles (0.6 mW control field power) and squares (2 mW control field power) are the measured delayed phases and the open circles (0.6 mW control field power) and squares (2 mW control field power) are the expected delayed phases from equation 4 and group delay measurements.Motional sensing using atoms via atomic interference has reached very high precision and accuracy19,20. However, due to its nature of differential measurement it can only be sensitive to acceleration. Although two-photon Raman velocimetry can select a group of atoms with very narrow velocity width in an atomic ensemble determined by the duration of the pulse length21, it is not adequate to sense the collective motion of an atomic cloud. For the determination of the center-of-mass velocity of an atomic ensemble, one would be required to map out all the velocity groups and, therefore, the sensitivity is restricted to the Doppler broadening of the ensemble. Even in the high precision photon recoil frequency measurement using optical Bloch oscillation with 10−9 relative uncertainty22, it can only measures integers of one photon recoil frequency. For light dragging in an EIT medium, all atoms participate to the collective motion so that the velocity measurement is less sensitive to the Doppler broadening of the atomic ensemble.
Slow light in a three-level system can also be modelled as a dark state polariton: Ψ=cosθ(t′)ε(z,t′)−sinθ(t′)N1/2σ(z,t′)exp(ikeffz), where z is the spatial coordinate, t′ is time coordinate, ε(z,t′) is the electric field amplitude of probe field, N1/2σ(z,t′) is the collective atomic spin coherence, and the mixing angle θ(t′) is determined by the coupling strength and control field intensity23,24.
When the probe field enters the EIT medium, part of the probe field is converted into the collective spin coherence. Due to the motion of the atomic ensemble, the exponent exp(ikeffz) can be extended to exp[ikeff(zo+vt′)], where zo is the initial position of the ensemble25. After the probe field exits the ensemble, the collective atomic coherence is converted back to the probe field with an additional phase shift keffvt′, coincides with equation 4 as t is the group delay of the probe field.Our measured phase uncertainty is about 0.01 radians by taking the mean of three cycles of 70 MHz sinusoidal wave in the probe field envelope and averaging for 20 experimental cycles. Each experimental cycle takes 2 s and the duration is mainly limited by the time of loading the atomic ensemble and processing the data.
Using the value of the effective wavevector keff=1.61 × 107 m−1 and largest group delay time t=855(7) ns, our experiment demonstrates a velocimeter with sensitivity Δv=Δϕ/(keffτ) at the level of 1 mm s−1, two orders of magnitude higher than the velocity width Δva=(8kBTln2/m)1/2≈176 mm s−1 of our atomic ensemble, where kB is the Boltzmann constant, m is the mass of 85Rb, and T is the effective temperature of the atomic cloud. In principle, with our 1 μW of probe field, we should be able to increase the sensitivity by at least two orders of magnitude when we reach the shot noise limit at 5 × 10−4 radians per square root Hertz by recording all the cycles within the probe field. The sensitivity can also be improved by using larger atomic ensemble and smaller group velocity, that is, 1 cm of an atomic sample can improve our sensitivity to 100 μm s−1. Storage of the optical field in an atomic ensemble has reached a storage time close to a minute by either confining cold atomic vapour in an optical potential or placing a rare earth-ion-doped crystal at cryogenic temperature26,27. The sensitivity can be improved by seven orders of magnitude with successful implementation of the above methods. To measure the gravity with our velocimeter, equation 4 can be expressed as ϕ=−keffgt2. One second of the storage time can induce a phase shift of 108 radians, reaching the level of the current state-of-the-art phase shift of atom interferometer based inertial sensor28,29.In conclusion, we have demonstrated the largest Fizeau's light-dragging effect using a moving EIT medium and applied it for velocimetry. Tracing the velocity of a free-falling atomic ensemble at different timing, one can measure the acceleration as well.
Although the counter-propagating arrangement of the EIT fields in our experiment can only be implemented with cold atoms due to Doppler broadening of the ensemble15, this method can be extended to thermal atoms by using co-propagating arrangement, which is insensitive to the Doppler broadening of atoms to the first order. Our demonstration could lead to the study of inertial effect with a collective state of atoms and designing a new type of motional sensor.Consider a probe field travelling along a moving medium of velocity v, the dispersion relation in the rest frame readswhere k′ and ω′ are the wavenumber and the frequency of the probe field in the rest frame. Employing the Lorentz transformation to the first order of v/c, ω′=ω−kv, k′=k−ωv/c2, where k and ω are the wavenumber and frequency of the field in the laboratory frame, we expand the index of refraction n(ω′) in equation 5 in a power series of kv to the first orderDividing equation 6 by n/(ck), the phase velocity vp≡ω/k can be written as vp=c/n+Fdv, where Fd=1−1/n2+(ω/n)(n(ω)/ω) is the dragging coefficient.Experimental detailsOur medium is an ensemble of about 109 85Rb atoms after loading from a magneto-optical trap and the effective temperature is about 40 μK after sub-Doppler cooling. Due to the imbalance of radiation pressure from the cooling beams and gravity, the atomic cloud has an initial velocity before the EIT fields are sent in. Our push field is resonating on the 85Rb D2 line F=2 to F′=3 transition of the ensemble aided by an optical pumping field resonating on F=3 to F′=2 of D1 line to ensure atoms are returned to the original state. The pulse duration of the push field is 0.7 ms and the power is adjusted for varying the velocity. Atoms absorb photons from the push field in a well-defined direction and re-scatter them in a random direction. On average, atoms will gain a velocity proportional to the number of the photons being absorbed. The direction of the push field can be reversed for measurements of velocity at the opposite direction.
The velocity of the atomic cloud after the push field is measured using the time-of-flight method with a CCD (charge-coupled device) camera.The probe field has a waist of 300 μm positioned around the center of the atomic ensemble and the waist of the control field is about two times larger than the probe beam to ensure all the atoms interacting with the probe field are addressed by the control field with the same intensity. We align the control and the probe field at nearly counter-propagating direction (about 183 degrees). The wavevector k in equation 4 can be replaced by the effective wavevector keff=k−kcos183°. The control field is generated from a diode laser and part of the power is sent through an electro-optical modulator. The first sideband after the modulator passes through a solid Fabry-Pérot cavity followed by a 70 MHz acoustic-optical modulator. The field coming out of lower first order serves as the probe field and the zero order serves as an auxiliary field which then combines with the probe field by a polarizing beam splitter to form a 70 MHz beating signal. This 70 MHz signal is further split: part of the beam is sent through the atomic ensemble for the light-dragging experiment and the other half serves as a local oscillator for phase comparison as shown in Fig.
1b. Since the auxiliary field is 70 MHz detuned from the probe field, it does not experience the large light-dragging effect as the probe field and, therefore, the phase shift of the 70 MHz signal results from the phase velocity dragging of the probe field only.After 5 ms of turning off the magneto-optical trap, the push field is on followed by probe and control field. The probe field intensity is about 1 μW and its amplitude is modulated by a Gaussian function of 9 μs full width at half maximum. The control field is turned on 300 μs before the probe field to ensure atoms are prepared in the F=2 state.Data availabilityThe data that support the findings of this study are available from the corresponding author upon reasonable request.How to cite this article: Kuan, P.-C. et al.
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