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First measurements of the index of refraction of gases for lithium atomic waves

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We report here the first measurements of the index of refraction of gases for lithium waves. Using an atom interferometer, we have measured the real and imaginary part of the index of refraction n for argon, krypton and xenon, as a function of the gas density for several velocities of the lithium beam. The linear dependence of $(n-1)$ with the gas density is well verified. The total collision cross-section deduced from the imaginary part is in very good agreement with traditional measurements of this quantity. Finally, as predicted by theory, the real and imaginary parts of $(n-1)$ and their ratio ρ exhibit glory oscillations.

The index of refraction of matter has been extended from light waves to neutron waves around 1940. The next step, which was to extend this concept to atom waves, has been done in 1995 by D. Pritchard and co-workers who made the first measurements of an index of refraction n of gases for sodium waves [1]. This group has also studied the variations of the index of refraction with sodium velocity, thus observing glory oscillations [2, 3].

Several papers [4, 5, 6, 7, 8, 9, 10, 11, 12, 13] deal with the theory of the index of refraction n and its calculation which requires the knowledge of the interaction potential between an atom of the wave and an atom of the target gas. The index of refraction is related to the forward scattering amplitude, which exhibits many resonances at low energies and glory oscillations. If the target gas is at ordinary temperature, the thermal averaging has important effects and all the resonances as well as most of the glory oscillations are washed out. Finally, in the low density regime, $(n-1)$ is a linear function of the gas density n_{gas} .

We report here the first measurements of the index of refraction of gases for lithium waves, with an experiment similar to the experiment of D. Pritchard and co-workers [1, 2, 3]. However, in these experiments, the value of the gas column density was not directly known and their main experimental result was the ratio $\rho = \mathcal{R}e(n-1)/\mathcal{I}m(n-1)$ of the real and imaginary parts of $(n-1)$. In our experiment, the gas column density is known with a good accuracy, so that we can measure separately the real and imaginary parts of $(n-1)$. We have deduced the total cross-section from our measurements of the imaginary part $\mathcal{I}m(n-1)$ and our values are in very good agreement with the very accurate measurements by L. Wharton and co-workers, using scattering techniques [21, 22].

The principle of the experiment is to introduce some gas on one of the atomic beams inside an atom interferometer, as represented in figure 1. Noting $\psi_{u/l}$ the waves propagating on the upper/lower paths inside the interferometer, the interference signal I is given by:

$$I = |\psi_l + \psi_u \exp(i\varphi)|^2 \quad (1)$$

where the phase φ depends on the grating positions ($\varphi = k_G(2x_2 - x_1 - x_3)$ where k_G is the grating wavevector and x_i measures the position of grating i). We can rewrite equation (1) as:

$$I = I_B + I_0 [1 + \mathcal{V} \cos(\varphi)] \quad (2)$$

I_0 is the mean intensity, \mathcal{V} the fringe visibility and we have added the detector background I_B . The fringe visibility differs from $\mathcal{V} = 1$, because of an imperfect balance of the two beams and mostly because of a noise on φ due to vibrations [15].

When the atomic wave propagates in a gas of density n_{gas} , the index of refraction n modifies the atom wave vector \mathbf{k} which becomes $n\mathbf{k}$. For a gas cell of length L in the upper path, the wave ψ_u is replaced by the transmitted wave $\psi_{u,t}$ given by:

$$\psi_{u,t}/\psi_u = e^{i(n-1)kL} = t(n_{gas})e^{i\varphi(n_{gas})} \quad (3)$$

with $t(n_{gas}) = \exp[-\mathcal{I}m(n-1)kL]$ and $\varphi(n_{gas}) = \mathcal{R}e(n-1)kL$. The signal given by equation (2) is modified, with a phase shift equal to $\varphi(n_{gas})$. The mean intensity $I_0(n_{gas})$ and the fringe visibility $\mathcal{V}(n_{gas})$ are both changed and $t(n_{gas})$ is related to these quantities by:

$$t(n_{gas}) = \frac{I_0(n_{gas})\mathcal{V}(n_{gas})}{I_0(0)\mathcal{V}(0)} \quad (4)$$

Our experimental setup is centered on a Mach-Zehnder atom interferometer using laser diffraction of lithium in the Bragg regime [14]. The laser wavelength is close to the lithium first resonance line at 671 nm. In order to optimize our interferometer for ${}^7\text{Li}$ isotope and first order diffraction, we use the following standing wave parameters: a frequency detuning equal to 4 GHz, a total laser

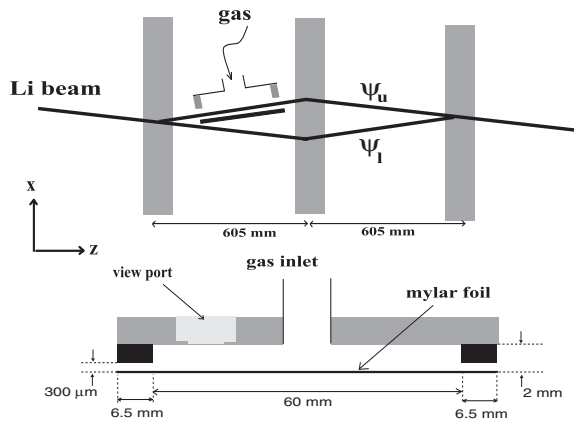


FIG. 1: Upper part: schematic drawing of a top view of the interferometer, with the gas cell inserted just ahead of the second laser standing wave. Lower part: top view of the gas cell. The view-port is used to align the septum by optical techniques. The slit widths are exaggerated to be visible.

power equal to 275 mW and a beam waist radius $w_0 = 6.2$ mm. By seeding lithium in a rare gas mixture, we can vary the lithium beam mean velocity u .

Just ahead of the second laser standing wave, the distance between the atomic beam centers is close to $90 \mu\text{m}$ when $u = 1075$ m/s and this distance is sufficient to insert a septum between these beams. The septum, a $6 \mu\text{m}$ thick mylar foil, separates the gas cell from the interferometer vacuum chamber. In order to reduce the gas flow out of the cell, the cell is connected to the interferometer chamber by $300 \mu\text{m}$ wide slits as shown in Fig. 1. The cell is made of aluminium ultra-high vacuum gas line to a leak valve used to introduce the gas. An other valve connects the gas line to the interferometer vacuum chamber so that the pressure in the gas cell can be reduced to its base value in about 3 s.

For the measurements, we use high purity gases from Air Liquide (total impurity content below 50 ppm), with a cell pressure in the $10^{-3} - 10^{-4}$ millibar range. This pressure is measured by a membrane gauge (CERAVAC CTR91 from Leybold), with a stated accuracy better than 1% in the middle of this pressure range. When the cell is evacuated, the measured pressure is negligible $p_{meas.} = (1 \pm 1) \times 10^{-6}$ millibar, near the gauge sensitivity limit. Because of the gas flow through the connection pipe and the slits, the pressure in the cell p_{cell} is slightly less than the value $p_{meas.}$ measured by the gauge located at about 50 cm from the gas cell. Molecular flow theory predicts $p_{cell}/p_{meas.} = C_{pipe}/(C_{pipe} + C_{slits})$ where C_{pipe} and C_{slits} are the vacuum conductances of the pipe and the slits. Using calculated conductance values, we get $p_{cell}/p_{meas.} = 0.90 \pm 0.01$. The gas density n_{gas} in the cell is deduced from the pressure p_{cell} by the ideal gas law at a 298 K temperature.

We record interference fringes by applying a linear voltage ramp on a piezo-electric stage carrying the mirror

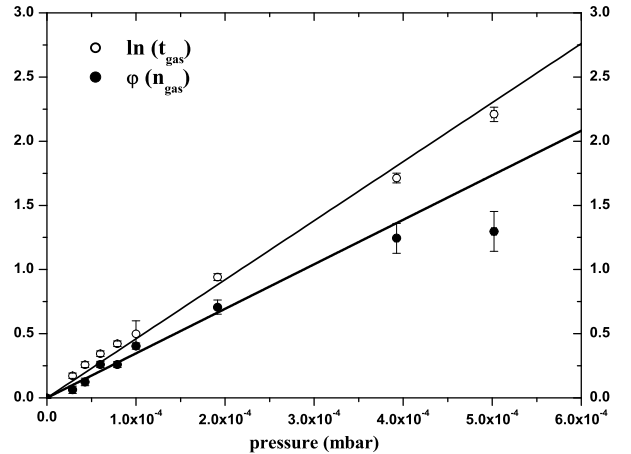


FIG. 2: Plot of the measured values of the phase shift $\varphi(n_{gas})$ and of the logarithm of the amplitude transmission $\ln(t(n_{gas}))$ as a function of the xenon pressure p_{cell} . The lithium beam mean velocity is $u = 1075 \pm 20$ m/s.

of the third standing wave, thus sweeping the grating phase φ . During an experiment, we make three successive recordings, the first one ($j = 1$) with an empty cell, the second one ($j = 2$) with a pressure p_{cell} and the third one ($j = 3$) with an empty cell, so that we can correct the interferometer phase drift. The counting time is 0.3 s per data point, with 300 points per recording. At the end of the three recordings, we flag the lithium beam to measure the detector background I_B . We assume that the phase φ can be written $\varphi = a_j + b_j n + c_j n^2$, where n is the channel number and the quadratic term describes the non-linearity of the piezo stage. Each recording is fitted by equation 2 and the best fit provides its initial phase a_j , its mean intensity I_{0j} and its fringe visibility \mathcal{V}_j . We then extract the effects of the gas present during the second recording by calculating the phase shift $\varphi(n_{gas})$, using $\varphi(n_{gas}) = a_2 - (a_1 + a_3)/2$, and the wave amplitude attenuation $t(n_{gas})$, using equation (4), the zero pressure value of $I_0(0)\mathcal{V}(0)$ is taken as the mean of the $j = 1$ and $j = 3$ recordings.

To make a measurement of the index of refraction for a given lithium velocity u , we measure the phase shift $\varphi(n_{gas})$ and the wave amplitude attenuation $t(n_{gas})$ for various pressures in the cell and we plot these two quantities as a function of the pressure (see figure 2). The phase shift $\varphi(n_{gas})$ and the logarithm of the amplitude transmission $\ln(t(n_{gas}))$ vary linearly with gas pressure, as expected from theory. This linear relationship was verified by D. Pritchard and co-workers [1, 2, 18], but not as directly as in the present work and their signal to noise ratio was less good than ours.

To deduce $\text{Re}(n - 1)$ and $\text{Im}(n - 1)$ from $\varphi(n_{gas})$ and $t(n_{gas})$, we need the kL value. To get k , we measure the lithium beam velocity u by Bragg diffraction. The effective cell length L is calculated by weighting each element dz of the beam path by the local gas density. In the molecular regime, the density in the slits varies linearly

with the distance and vanishes near the slit exit (this result was used to describe the flow in multi-capillary channels [19]). The effective length L is then the sum of the internal part length and of the mean of the slit lengths, $L = 66.5 \pm 1.0$ mm. Our final results are the real and imaginary parts of $(n-1)$ divided by the gas density and the ratio $\rho = \mathcal{Re}(n-1)/\mathcal{Im}(n-1)$. These results are collected in table I for a lithium velocity $u = 1075 \pm 20$ m/s and we have similar data for several other velocities.

gas	Ar	Kr	Xe
$10^{29}\mathcal{Re}(n-1)/n_{gas}$	1.20 ± 0.11	1.57 ± 0.10	1.82 ± 0.07
$10^{29}\mathcal{Im}(n-1)/n_{gas}$	2.11 ± 0.06	1.99 ± 0.07	2.40 ± 0.06
ρ	0.56 ± 0.05	0.78 ± 0.04	0.70 ± 0.03

TABLE I: Measured values of the index of refraction of argon, krypton and xenon for lithium waves at a velocity $u = 1075 \pm 20$ m/s. We give the real and imaginary parts of $10^{29}(n-1)/n_{gas}$, with n_{gas} in m^{-3} , and the ratio $\rho = \mathcal{Re}(n-1)/\mathcal{Im}(n-1)$, which is dimensionless.

The imaginary part of the index of refraction, which measures the attenuation of the atomic beam by the gas, is related to the total collision cross section $\langle\sigma\rangle$ by $\langle\sigma\rangle = 2\mathcal{Im}(n-1)k/n_{gas}$ where $\langle..\rangle$ designates the average over the target gas thermal velocity. We have thus deduced the total collision cross section $\langle\sigma\rangle$, which can be compared with the measurements of L. Wharton and co-workers [21, 22] made by measuring the transmission of an atomic beam through a gas cell. Figure 3 presents these two measurements in the case of xenon and the agreement is very good, although the velocity distribution of our lithium beam, with a full width at half maximum close to 25%, is broader than the 4.4% FWHM distribution used by Wharton and co-workers.

From theory [3, 12, 13], we know that the real and imaginary parts of $(n-1)$ decrease rapidly with the lithium velocity u , like $u^{-7/5}$, with glory oscillations superimposed on this rapid variation. We have chosen to plot the real and imaginary parts of $u^{7/5}(n-1)/n_{gas}$ so as to suppress this rapid dependence. Our results, which appear in figure 4, show very clearly glory oscillations and we can verify that the oscillations of the real and imaginary parts of $(n-1)$ are almost in quadrature, as expected from theory [12].

Figure 5 compares our measurements of the ratio $\rho = \mathcal{Re}(n-1)/\mathcal{Im}(n-1)$ with theoretical predictions in the case of xenon for which we have more data points. The mean ρ value is close to, but slightly lower than, the $\rho = 0.72$ value predicted by the group of D. Pritchard [1, 2] for a purely attractive r^{-6} long range potential. A lower mean value of ρ is expected when the $n = 8$ and 10 terms of the r^{-n} expansion of the potential are also attractive and not negligible [12]. Moreover, a glory oscillation is clearly visible on our measurements and we can compare this observation with the calculations done by C. Champenois in her thesis [13] with three different potential curves taken from the literature : two ab initio

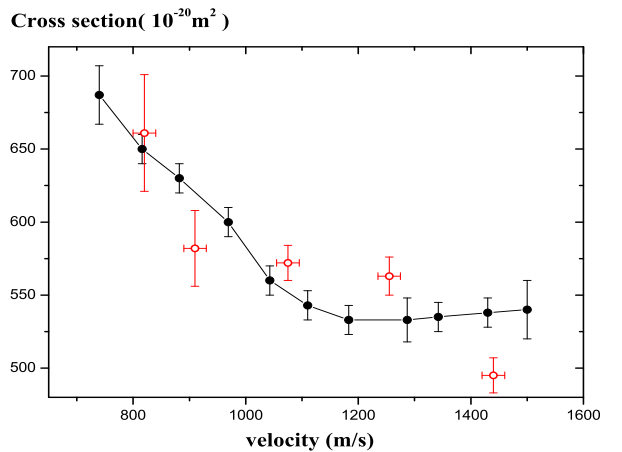


FIG. 3: Plot of the measured values of lithium-xenon total collision cross section $\langle\sigma\rangle$ as a function of the lithium mean velocity u . The dots represent the data points of Dehmer and Wharton copied from figure 6 of ref. [22] (as there are several data points for each velocity, we use the extreme data points to define an error bar and their mean as the measured value) and the open circles represent our measurements by atom interferometry.

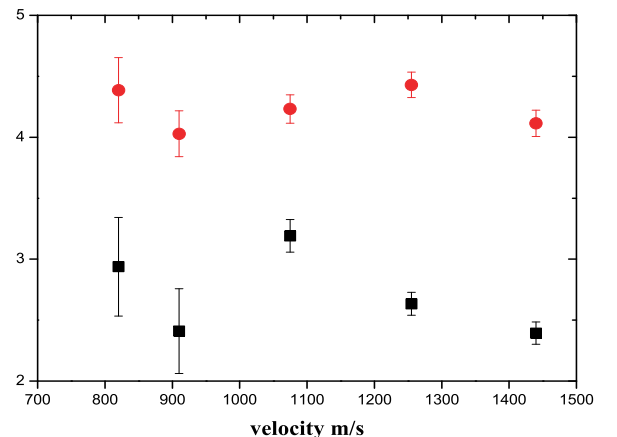


FIG. 4: Plot of the measured values of the real (squares) and imaginary (dots) parts of $10^{25}u^{7/5}(n-1)/n_{gas}$ for xenon as a function of the lithium beam mean velocity u (n_{gas} in m^{-3} and u in m/s). The glory oscillations are clearly visible and almost in quadrature.

potentials [23, 24] and a semi-empirical one [22]. The experimental amplitude of the glory oscillation is comparable to the theoretical amplitudes for all three potentials but the experimental phase of this oscillation is close to the phase of the calculated glory oscillations for the potentials of references [22, 23] and not for the potential of reference [24]. The total number of glory oscillations and their phase is very sensitive to the potential well depth and more precisely to the number of vibrational levels and this explains the difference between the calculated curves.

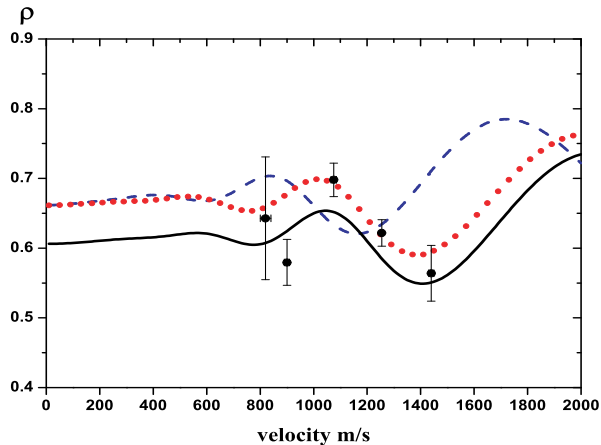


FIG. 5: Plot of the measured values of ratio $\rho = \text{Re}(n - 1)/\text{Im}(n - 1)$ for xenon as a function of the lithium beam mean velocity u . The points are our experimental values while the curves have been calculated with three different lithium-xenon potential curves : full line [22], dotted line [23] and dashed line [24].

In this letter, we have described the first measurements of the index of refraction of gases for lithium waves. An open gas cell is introduced on one of the atomic beams inside an atom interferometer and the propagation in the gas modifies the phase, the mean intensity and the visibility of the interference fringes. From the measurement of these three quantities, we have deduced the real and imaginary parts of the index of refraction n . Thanks to an accurate measurement of the gas density, we have verified that $(n - 1)$ is a linear function of the gas density with a good accuracy. We have measured the real and imaginary parts of $(n - 1)/n_{gas}$ as well as the ratio $\rho = \text{Re}(n - 1)/\text{Im}(n - 1)$ for three gases and several lithium velocities, with a relative uncertainty in the 5 – 10% range.

We hope to improve our experiment, in particular the

gas cell: the septum casts a too large shadow which limits our ability to use a higher velocities of the lithium beam. We are building a new gas cell of better quality and it is also possible to operate our interferometer with second order diffraction [14], thus doubling the distance between the atomic beams and increasing substantially the place available for the septum. We thus hope to measure the index of refraction in a large velocity range, to study several other gases and to improve the accuracy of the measurements.

We have tested our measurements by comparing previous measurements of the total cross-section with the imaginary part of the index of refraction. For the real part, which can be measured only by atom interferometry, we have used theoretical considerations and these two tests have been very satisfactory. Moreover, the comparison between experimental and theoretical values of the ratio $\rho = \text{Re}(n - 1)/\text{Im}(n - 1)$ is already able to favor certain interaction potentials available in the literature with respect to an other one. Obviously, with a slightly improved accuracy and more data points covering a wider velocity range, the measurements of the index of refraction can provide a stringent test of existing interaction potentials. However, it seems clear that a very accurate potential cannot be obtained by inversion of index of refraction measurements if one cannot reduce the effect of thermal averaging which washes out the low-energy resonances and most of the glory oscillations.

Acknowledgments

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