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Measurement of the electric polarizability of lithium by atom interferometry

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We have built an atom interferometer and, by applying an electric field on one of the two interfering beams, we have measured the static electric polarizability of lithium $\alpha = (24.33 \pm 0.16) \times 10^{-30} \text{ m}^3$ with a 0.66% uncertainty. Our experiment is similar to an experiment done on sodium in 1995 by D. Pritchard and co-workers, with several improvements: the electric field can be calculated analytically and our phase measurements are very accurate. This experiment illustrates the extreme sensitivity of atom interferometry: when the atom enters the electric field, its velocity increases and the fractional change, equal to 4×10^{-9} for our largest field, is measured with a 10^{-3} accuracy.

An atom interferometer is the ideal tool to measure any weak modification of the atom propagation due to electromagnetic or inertial fields. The application of a static electric field is particularly interesting because it gives access to the electric polarizability α and this quantity cannot be measured by spectroscopy which is sensitive only to polarizability differences (for a review on polarizability measurements, see reference [1]).

Several experiments with atom interferometers have exhibited a sensitivity to the electric electric field [2, 3, 4] without aiming at a polarizability measurement and interferometers using an inelastic diffraction process have been used to measure the difference of polarizability between the ground state and an excited state [5, 6]. A very accurate measurement of the atom polarizability α requires that a well-defined electric field is applied on only one interfering beam and, up-to-now, such an experiment has been made only by D. Pritchard et al. [7, 8] by inserting a thin electrode, a septum, between the two atomic paths. We have made a similar experiment with our lithium atom interferometer, represented in figure 1

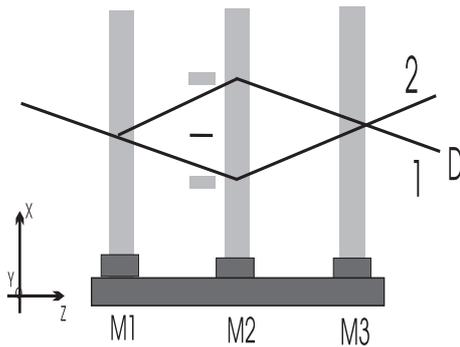


FIG. 1: Schematic drawing of our Mach-Zehnder atom interferometer: a collimated atomic beam, coming from the left, is diffracted by three laser standing waves and the output beam 1 selected by a slit is detected by a hot-wire detector D. The capacitor with a septum is placed just before the second laser standing wave. The x, y and z axis are defined.

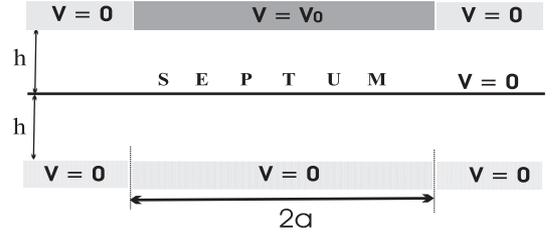


FIG. 2: Schematic drawing of the capacitor. The septum is parallel to the z -axis and the electrodes are located at $x = \pm h \approx 2 \text{ mm}$. The high voltage electrodes at the potential V_0 extends from $z = -a$ to $z = +a$, while the guard electrodes extend outside with $|z| > a$, with $a \approx 25 \text{ mm}$. The septum and the guard electrodes are at $V = 0$.

and we are going to describe its first results. With respect to the experiment of D. Pritchard et al., we have made several improvements: we have designed a capacitor with an analytically calculable electric field; we have a better phase sensitivity; finally our interferometer based on laser diffraction is species selective. Our experimental accuracy is presently limited by the knowledge of the mean atom velocity.

When an electric field E is applied, the ground state energy decreases by the polarizability term $U = -2\pi\epsilon_0\alpha E^2$. Therefore, when an atom enters the electric field, its kinetic energy increases and its wave vector k becomes $k + \Delta k$, with $\Delta k = 2\pi\epsilon_0\alpha E^2 m / (\hbar k)$. The resulting phase shift ϕ of the atomic wave is given by:

$$\phi = \frac{2\pi\epsilon_0\alpha}{\hbar v} \int E^2(z) dz \quad (1)$$

$v = \hbar k / m$ is the atom velocity and the spatial dependence of the electric field along the atomic path is taken into account.

To know precisely the electric field along the atomic path, guard electrodes are needed, as discussed in [7]. We have developed a capacitor where guard electrodes are in the plane of the high voltage electrode, as shown

in figure 2, which defines the notations. In this case, the field can be expressed analytically from the potential distribution $V(z, x = h)$ in the plane of the high-voltage electrode. We give here only the results of the calculation which will be published elsewhere [9].

The integral of E^2 along the septum surface can be written :

$$\int E(z, 0)^2 dz = \left[\frac{V_0}{h} \right]^2 L_{eff} \quad (2)$$

V_0/h is the electric field of an infinitely long capacitor and the capacitor effective length L_{eff} is given by:

$$L_{eff} \approx 2a - (2h/\pi) \quad (3)$$

where exponentially small corrections of the order of $\exp(-2\pi a/h)$ are neglected. The atoms do not sample the electric field on the septum surface but at a small distance x from the septum and we should add to the effective length a small correction proportional to x^2 . In our experiment, with $x \lesssim 50 \mu\text{m}$ and $h \approx 2 \text{ mm}$, this correction is below $10^{-4}L_{eff}$ and negligible.

The capacitor external electrodes are made of thick glass plates covered by an aluminium layer. The guard electrodes are insulated from the high voltage electrode by $100 \mu\text{m}$ wide gaps which have been made by laser evaporation and, under vacuum, we can operate the capacitor up to $V = 450 \text{ V}$. The glass spacers are glued on the external electrodes and the septum, made of a $6 \mu\text{m}$ thick mylar foil aluminized on both faces, is stretched and glued on the electrode-spacer assemblies. In our calculation, we assume that the potential on the high-voltage electrode is known everywhere but we ignore the potential inside the $100 \mu\text{m}$ wide dielectric gaps which may get charged. A superiority of our design is that these gaps are very narrow, thus minimizing the uncertainty on the capacitor effective length. Another defect is that the spacer thicknesses are not perfectly constant. We use equation (2) by replacing h by its mean value $\langle h \rangle$, thus making a relative error of the order of $\langle (h - \langle h \rangle)^2 \rangle / \langle h \rangle^2$ which is fully negligible.

We have previously described our three-grating Mach-Zehnder atom interferometer [10, 11]. The lithium atomic beam is a supersonic beam seeded in argon and we use Bragg diffraction on laser standing waves at $\lambda = 671 \text{ nm}$. By choosing a laser detuned by about 3 GHz on the blue side of the $^2S_{1/2} - ^2P_{3/2}$ transition of the ^7Li isotope, the signal is almost purely due to this isotope (natural abundance 92.4%) and not to the other isotope ^6Li . Any other species present in the beam, for instance lithium dimers or heavier alkali atoms, is not diffracted and does not contribute to the signal. In three-grating interferometers, the phase of the interference fringes depends on the x -position of the gratings depending themselves on the position x_i of the mirrors M_i forming the three laser standing waves and this phase is given by

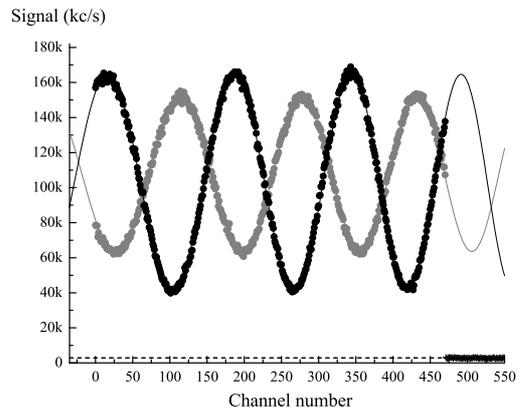


FIG. 3: Experimental signals and their fits (full curves) corresponding to $V = 0$ (black dots) and $V_0 \approx 260 \text{ Volts}$ (grey dots): the phase shift is close to 3π with a reduced visibility.

$\psi = 2pk_L(x_1 + x_3 - 2x_2)$, where k_L is the laser wavevector and p is the diffraction order. By scanning the position x_3 of mirror M_3 , we have observed interference fringes with an excellent visibility \mathcal{V} , up to 84.5%.

The capacitor is placed just before the second laser standing wave, with the septum between the two atomic beams. In the present work, we have used only the diffraction order $p = 1$ so that the center of the two beams are separated by about $90 \mu\text{m}$ in the capacitor. When the septum is inserted between the two atomic paths, the atom propagation is almost not affected and we observe interference fringes with a visibility $\mathcal{V} = 84 \%$ and a negligible reduction of the atomic flux. To optimize the phase sensitivity, we have opened the collimation slit S_1 and the detection slit S_D (see reference [11]) with widths $e_1 = 18 \mu\text{m}$ and $e_D = 50 \mu\text{m}$, thus increasing the mean flux up to 10^5 counts/s and slightly reducing the fringe visibility down to $\mathcal{V}_0 = 62\%$ (see figure 3). We have made a series of recordings, labelled by an index i from 1 to 44, with $V_0 = 0$ when i is odd and with $V_0 \neq 0$ when i is even with $V_0 \approx 10 \times i \text{ Volts}$. For each recording, we apply a linear ramp on the piezo-drive of mirror M_3 in order to observe interference fringes and 471 data points are recorded with a counting time per channel equal to 0.36 s. Figure 3 presents a pair of consecutive recordings. The high voltage power supply has stability close to 10^{-4} and the applied voltage is measured by a HP model 34401A voltmeter with a relative accuracy better than 10^{-5} .

The data points $I_i(n)$ have been fitted by a function $I_i(n) = I_{0i} [1 + \mathcal{V}_i \cos \psi_i(n)]$, with $\psi(n) = a_i + b_i n + c_i n^2$ where n labels the channel number, a_i represents the initial phase of the pattern, b_i an ideal linear ramp and c_i the non-linearity of the piezo-drive. For the $V = 0$ recordings, a_i , b_i and c_i have been adjusted as well as the mean intensity I_{0i} and the visibility \mathcal{V}_i , while, for the $V \neq 0$ recording, we have fitted only a_i , I_{0i} and \mathcal{V}_i , while fixing b_i and c_i to their value b_{i-1} and c_{i-1} from the previous $V = 0$ recording. Our best phase measurements are given by the mean phase $\langle \psi_i \rangle$ obtained by averaging

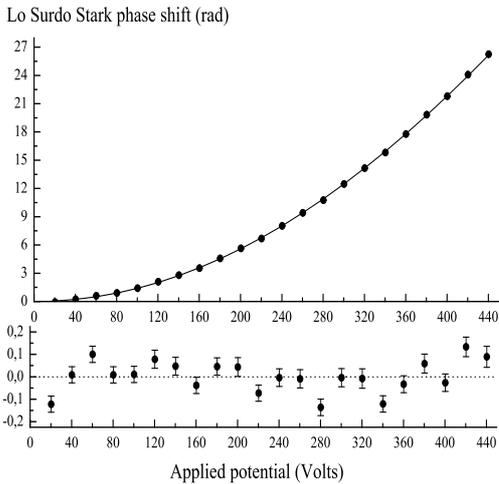


FIG. 4: Phase shift $\phi(V_0)$ as a function of the applied voltage V_0 : the best fit using equations (4,5) is represented by the full curve and the residuals are plotted in the lower graph.

$\psi_i(n)$ over the 471 channels. The 1σ error bar of these mean phases are of the order of 2 – 3 mrad, increasing with the applied voltage up to 23 mrad because of the reduced visibility.

The mean phase values $\langle\psi_i\rangle$ values of the $V_0 = 0$ recordings present a drift equal to 7.5 ± 0.2 mrad/minute and some scatter around this regular drift. The drift is explained by the differential thermal expansion of the structure supporting the three mirrors: its temperature was steadily drifting at 1.17×10^{-3} K/minute during the experiment. We have no explanation of the phase scatter, which presents a quasi-periodic structure: its rms value is equal to 33 milliradian and unfortunately this error dominates our phase determination.

The phase shift $\phi(V_0)$ due to the polarizability effect is taken equal to $\phi(V_0) = \langle\psi_i\rangle - (\langle\psi_{i-1}\rangle + \langle\psi_{i+1}\rangle)/2$ where the recording i corresponds to the applied voltage V_0 : the average of the mean phase of the two $V_0 = 0$ recordings done just before and after is our best estimator of the mean phase of the interference signal in zero field. In figures 4 and 5, we have plotted the phase shift $\phi(V_0)$ and the fringe visibility \mathcal{V} as a function of the applied voltage V_0 .

To interpret these results, we must take into account the velocity distribution of the lithium atoms, as the phase shift is proportional to v^{-1} . We assume that the velocity distribution is given by:

$$P(v) = \frac{S_{\parallel}}{u\sqrt{\pi}} \exp\left[-((v-u)S_{\parallel}/u)^2\right] \quad (4)$$

with the most probable velocity u and S_{\parallel} is the parallel speed ratio. The traditional v^3 pre-factor [12], which has minor effects, is omitted when S_{\parallel} is large. The interference signals I can be written:

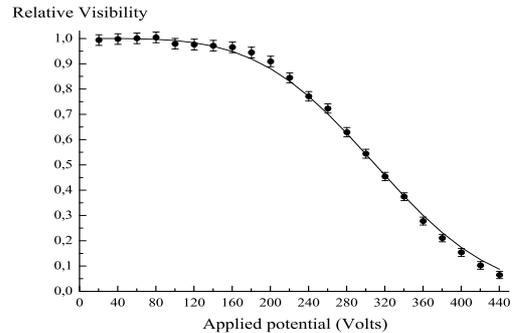


FIG. 5: Relative fringe visibility $\mathcal{V}/\mathcal{V}_0$ (with $\mathcal{V}_0 = 62\%$) as a function of the applied voltage V_0 and the best fit using equations (4,5) (full curve).

$$I = I_0 \int dv P(v) \left[1 + \mathcal{V}_0 \cos\left(\psi + \phi_m \frac{u}{v}\right)\right] \quad (5)$$

with $\phi_m = \phi(u)$. If we expand u/v in powers of $(v-u)/u$ up to second order, the integral can be calculated exactly. This approximation is very good [9] but not accurate enough and we have calculated the integral (5) numerically. We have thus made a single fit for the phase and visibility results, with two adjustable parameters: ϕ_m/V_0^2 and S_{\parallel} . As shown in figures 4 and 5, the agreement is very good, in particular for $\langle\phi\rangle$, and we deduce a very accurate value ϕ_m/V_0^2 :

$$\frac{\phi_m}{V_0^2} = \frac{2\pi\epsilon_0\alpha L_{eff}}{\hbar u \langle h \rangle^2} = (1.3870 \pm 0.0010) \times 10^{-4} \text{ rad/V}^2 \quad (6)$$

The relative uncertainty 0.07% proves the coherence of our measurements. The parallel speed ratio $S_{\parallel} = 8.00 \pm 0.06$ is slightly larger than expected for our lithium beam, because Bragg diffraction is velocity selective.

From measurements made on our capacitor, we get $2a = 50.00 \pm 0.10$ mm and $\langle h \rangle = 2.056 \pm 0.003$ mm. We have measured the mean velocity u using Doppler effect, by recording atom deflection due to photon recoil with a laser beam almost counterpropagating with the atoms. The uncertainty on the cosine of the angle is negligible (0.12%) and we get $u = 1066.4 \pm 8.0$ m/s. We have also recorded the diffraction probability as a function of the Bragg angle, by tilting the mirror forming a standing wave. Using an independent calibration of the mirror rotation as a function of the applied voltage on the piezo-drive, we get a measurement of the Bragg angle $\theta_B = h/(mu\lambda_L) = 79.62 \pm 0.63$ μ rad corresponding to $u = 1065.0 \pm 8.4$ m/s. These two values are perfectly coherent and we take the mean velocity as their weighted average $u = 1065.7 \pm 5.8$ m/s. The theory of supersonic expansion can be used to check this result: the velocity of a pure argon beam given by $u = \sqrt{5k_B T_0/m}$ (where $T_0 = 1073 \pm 11$ K is the nozzle temperature and m the

argon atomic mass) must be corrected: the dominant correction is the velocity slip effect estimated to be 1% [13] and we get $u = 1068.4 \pm 5.5$ m/s in very good agreement with our measurements.

Finally, we get the lithium electric polarizability of ${}^7\text{Li}$ $\alpha = (24.33 \pm 0.16) \times 10^{-30}$ m³, in excellent agreement with the previous measurements, $\alpha = (22. \pm 2.) \times 10^{-30}$ m³ by Chamberlain and Zorn [15] in 1963 and $\alpha = (24.3 \pm 0.5) \times 10^{-30}$ m³, by Bederson and co-workers [14] in 1974. Our result compares also very well with ab initio calculations of α : most calculations predict α values in the range $(24.32 - 24.45) \times 10^{-30}$ m³ (see reference [16] and references therein).

With respect to the experiment done on sodium by D. Pritchard and co-workers [7], we have made several important improvements:

Our capacitor design provides an analytical calculation of the E^2 integral along the atomic path. This property is helpful in minimizing the uncertainty on this quantity, through a better understanding of the influence of small defects. With an improved construction, we expect to reduce the uncertainty on this integral below 0.1 %, the main limitation being due to the unknown potential in the dielectric gaps.

Thanks to a large signal and an excellent fringe visibility, the phase sensitivity of our interferometer is considerably larger than previously achieved. The accuracy on phase measurement is presently limited by the lack of reproducibility of the mean phase of the recordings. We hope to improve this reproducibility by stabilizing the temperature of the rail supporting the three mirrors. The consistency and accuracy of our phase measurements is proved by the quality of the fit of figure 4 and by the 0.07% uncertainty obtained for the measurement of ϕ_m/V_0^2 . We have deduced the value of the electric polarizability α with a 0.66% relative uncertainty dominated by the uncertainty on the mean atom velocity u .

Our interferometer is species selective thanks to laser

diffraction and this is also a very favorable circumstance. In his thesis, T. D. Roberts reanalyzes the measurement of sodium atom electric polarizability made by C. R. Ekstrom et al. [7]: he estimates that a weak contribution of sodium dimer to the interference signals might have introduced a non negligible systematic error in the result.

T. D. Roberts et al. [8] have devised a very clever technique to correct for the velocity dependence of the phase shift $\Delta\phi$, so that they can observe fringes with a good visibility up to very large ϕ values. The present result proves that a very accurate measurement can be also made in the presence of an important velocity dispersion without any compensation of the associated phase dispersion, provided that the velocity distribution is taken into account in the analysis.

Finally, we would like to emphasize two very striking properties of atom interferometry. Our phase measurement consists in measuring the increase Δv of the atom velocity v when entering the field:

$$\frac{\Delta v}{v} = \frac{\lambda_{dB}}{L_{eff}} \times \frac{\phi}{2\pi} \quad (7)$$

$\Delta v/v$ is extremely small reaching only $\Delta v/v \approx 4 \times 10^{-9}$ for our largest field. Our ultimate sensitivity, close to a 3 mrad phase shift, corresponds to $\Delta v/v \approx 6 \times 10^{-13}$!

In the capacitor, the atom wavefunction samples two regions of space separated by ~ 100 μm with a macroscopic object lying in between and this situation extends over 10^{-4} second, without any loss of coherence. This consequence of quantum mechanics remains surprising!

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