Matter Neutrality Test Using a Mach-Zehnder Interferometer

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Abstract. Neutrality of atoms and neutrons is already well established, with upper limits on the residual charge close to $10^{-21}|q_e|$ where q_e is the electron charge. The present paper proves that the sensitivity of atom interferometry is sufficient to compete with these previous measurements, with the additional advantage of dealing with single isolated particles. An experiment involving a three grating Mach-Zehnder atom interferometer using Bragg diffraction on laser standing waves and a slow lithium atomic beam is discussed with some details. Its sensitivity and the systematic effects due to atomic polarisability are evaluated carefully.

1 Introduction

In this paper, we propose an experiment to test neutrality of isolated lithium atoms. Atom interferometry has been shown to be the ideal technique to measure weak interactions of an atom with its environment [1,2]. In particular, in 1991, Kasevich and Chu have mentionned the test of neutrality of atoms as a possible utilisation of their atomic interferometer [2]. As far as we know, no further details have been published. The experimental set-up we propose is based on a Mach-Zehnder atom interferometer like the ones developped by the research groups of D. Pritchard [3], Siu Au Lee [4], A. Zeilinger [5] and the one under construction in our group [6]. If the same uniform electric field $\boldsymbol{E}$ is applied on both arms of the interferometer, a phase shift of the interferometric signal will appear. This phase shift will be proportional to the residual charge of lithium atom and to the electric field $\boldsymbol{E}$.

The expected advantages of the proposed experiment are of three kinds. First, this experiment will operate on isolated atoms, thus avoiding all possible parasitic effects related to macroscopic samples. Second, its sensitivity is expected to be at least comparable and hopefully larger than the one achieved by the best previous experiments reported below. Third, one can perform the experiment with the two natural isotopes of lithium, ^{6}Li and ^{7}Li and comparing these two results will lead to an independent measurement of neutron charge.

In the proposed configuration, a large modification of atomic propagation will be due to electric polarisability of lithium, but no phase shift should result if the apparatus is symmetric. Because this symmetry cannot be perfect, this will be the main systematic effect. Another possible arrangement, which also takes advantage of the Aharanov-Bohm effect [7], will be considered: in this arrangement, the two arms of the interferometer propagate inside equipotential volumes held at different potentials V_1 and V_2, so that the resulting phase-shift will be proportional to the residual lithium charge and to the potential difference $(V_1 - V_2)$. Because propagation occurs almost everywhere in a vanishing electric field, this arrangement will not suffer in principle from the systematic effect due to atomic polarisability.

In a first paragraph (part II), we recall the present knowledge concerning neutrality of atoms. Then (part III) we describe the proposed experimental method, its sensitivity, its main systematic errors and some possible refinements. Other possible experiments are briefly discussed (part IV) before the conclusion.

2 Neutrality of matter: present knowledge

Neutrality of atoms comes from two fundamental properties of their elementary constituents: equivalence of the absolute values of proton charge q_p and electron charge q_e, and neutrality of neutron. Both are essentially based on experimental data. An upper limit on the neutron charge q_n has been directly obtained by looking at the deflection of a neutron beam in an electric field [8]. The resulting limit is given by $|q_n| < 1.1 \times 10^{-21} \times |q_e|$ [8]. As reported by the Particle Data Group, the accepted value for the hydrogen atom charge $q_H = q_p + q_e$ is $|q_H| < 1 \times 10^{-21} \times |q_e|$ [9]. This limit is derived from a 1973 experiment which tested electrical neutrality of a gas of SF_6 [10]. An alternating electric field was applied to an acoustic cavity containing the molecular gas. If the SF_6 molecules had a residual charge, this would have generated a sound wave at the electric field frequency. A suitably calibrated microphone in the cavity measured the sound pressure. The resulting limit on the net charge of a SF_6 molecule was $1.9 \times 10^{-19} \times |q_e|$. In the general case of an atom or molecule with an atomic mass A and atomic number Z, charge conservation during nuclear and chemical reactions implies that the total charge $q_{A,Z}$ of the atom or molecule is

$$q_{A,Z} = Z(q_e + q_p) + (A - Z)q_n = Zq_H + (A - Z)q_n. \tag{1}$$

To derive their limit on $|q_H|$, the authors of ref. [10] assumed that neutron charge q_n is equal to hydrogen charge q_H, so that the limit on $|q_H|$ is simply the limit on the molecular charge divided by the total number A of nucleons of the molecule. The assumption $q_n = q_H$ comes from the assumption of charge conservation in neutron beta decay:

$$n \to p + e + \overline{\nu_e}, \tag{2}$$

with the additional assumption that the charge of electronic antineutrino $\overline{\nu_e}$ is exactly zero. This additional assumption looks questionable since the accepted limit [9] on the absolute value of the neutrino charge $q_{\overline{\nu_e}}$ is very poor compared with the accepted limit on q_n: $|q_{\overline{\nu_e}}| < 2. \times 10^{-15} \times |q_e|$. However, the limit on the SF_6 residual charge can still give a very good limit on $|q_H|$ without this assumption by using the experimental limit on $|q_n|$ obtained in 1988. From equation (1) one gets:

$$\left|\frac{q_H}{q_e}\right| < \frac{1}{Z}\left(\left|\frac{q_{SF_6}}{q_e}\right| + (A-Z)\left|\frac{q_n}{q_e}\right|\right). \tag{3}$$

In the case of SF_6, $A = 146$ and $Z = 70$. The resulting limit on $|q_H|$ is thus $|q_H/q_e| < 3.8\times10^{-21}$. On the other hand, charge conservation applied to neutron beta decay proves that $q_n = q_H + q_{\overline{\nu}}$, from which we can deduce an interesting limit on neutrino charge. Equation (1) can then be written:

$$q_{A,Z} = Aq_n - Zq_{\overline{\nu_e}} \tag{4}$$

and as far as limits are concerned

$$\left|\frac{q_{\overline{\nu_e}}}{q_e}\right| < \frac{1}{Z}\left(\left|\frac{q_{SF_6}}{q_e}\right| + A\left|\frac{q_n}{q_e}\right|\right). \tag{5}$$

The corresponding upper bound for neutrino charge is $|q_{\overline{\nu_e}}/q_e| < 5.2\times10^{-21}$.

In the past 27 years, only one experiment, aimed at searching for free fractional charges, gave also a limit on q_H [11]. The authors studied the motion induced by an electric field on several steel spheres kept in magnetic levitation. The experimental limit on the residual charge of a 0.2 mm diameter sphere was around $1.6\times10^{-2}\,|q_e|$. To derive the published limit on $|q_H|$, $|q_H/q_e| < 0.8\times10^{-21}$, the authors divided this residual charge by the nucleon number of the steel sphere equal to 1.97×10^{19}, implicitly assuming that neutrino charge exactly vanishes, as done in reference [10].

3 Experimental method

In the last years atom interferometry, and especially separated arms atomic interferometry, has proven to be a very sensitive tool for measuring atomic properties. Several configurations have been used. For example, the Ramsey-Bordé configuration [12] has allowed precise measurement of the atomic polarisability difference between the ground state and an excited long-lived state of magnesium [13] and calcium [14]. The three-grating Mach-Zehnder configuration has allowed the most precise measurement of electric polarisability of sodium atom in its ground state [1].

In figure 1, we show a scheme of the proposed experiment. A lithium atomic beam is optically pumped to one hyperfine level of its $^2S_{1/2}$ ground state and slowed down: its final mean velocity is noted v. The laser frequency is chosen to select a transition of one lithium isotope (natural abundances are 92.6% for ^{7}Li and 7.4% for ^{6}Li, but almost pure ^{6}Li is also available). After passing through two collimating slits and a chopper, the atomic beam is sent through three laser standing waves G_1, G_2, G_3 equally spaced by a distance L. Their frequency, intensities and thicknesses must satisfy the Bragg condition so that they behave like diffraction gratings for the atomic wave [4,15,16]. The grating period a is simply related to the laser wavelength λ_L by $a = \lambda_L/2$. Finally, in order to get the maximum signal and fringe contrast, the parameters of the three standing waves are adjusted so that G_1 and G_3 act as beam splitters with a 50% transmission and 50% reflexion coefficients, while grating G_2 behaves like completely reflecting mirrors, in order to form a symmetrical, diamond shaped, separated arms interferometer (see figure 1). The angle between the direct and diffracted beams will be noted θ_d. Assuming first order diffraction, this angle is simply $\theta_d = \lambda_{dB}/a$ where $\lambda_{dB} = h/mv$ denotes the de Broglie wavelength of the atoms. The outcoming beam is detected by collecting the laser induced fluorescence in a resonant light plane. The reader is referred to [6] for a more detailed description of the experimental setup.

As shown in figure 1, lithium residual charge q_{Li} will be measured by placing a parallel plate capacitor of length L_C between two gratings so that the two arms propagate symmetrically inside the field region. The semi-classical phase accumulated by a particle along the classical path Γ_{cl} in a potential $\mathcal{V}$ can be evaluated in the following way [17,18]:

$$\phi = -\int_{\Gamma_{cl}} \mathrm{d}t \frac{\mathcal{V}(\boldsymbol{r}(t), t)}{\hbar} \ . \tag{6}$$

The relevant potential here will be the electric potential expansion

$$\begin{aligned} \mathcal{V} &= \mathcal{V}_0 + \mathcal{V}_1 + \mathcal{V}_2 + ... & (7) \\ &= q_{Li} V - \boldsymbol{d} \cdot \boldsymbol{E} - \frac{1}{2} \alpha \boldsymbol{E}^2 + ... & (8) \end{aligned}$$

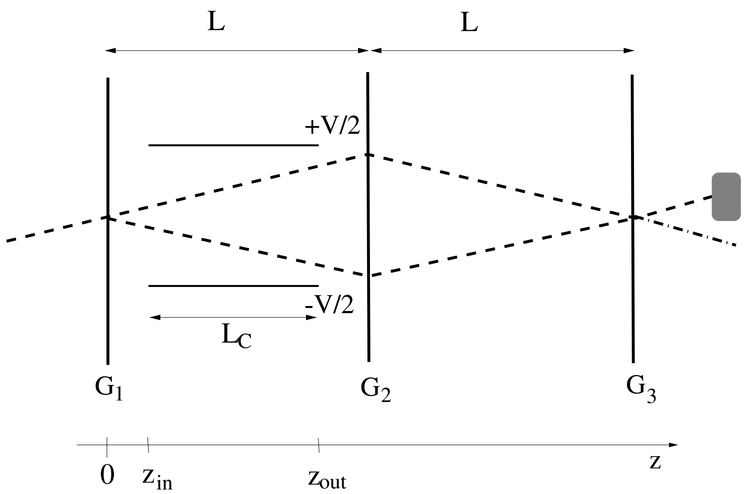

Fig. 1. The experimental set-up proposed to test neutrality of lithium atom is based on a Mach-Zehnder atom interferometer working in the Bragg configuration. G_1, G_2, G_3 are the three diffraction gratings and the detector is placed in front of one of the two complementary exits. The capacitor of length L_C extends from $z = z_{in}$ to $z = z_{out}$. Some plates defining the zero potential in a symmetrical way are not represented

where V and $\boldsymbol{E}$ respectively stand for the electric potential and field. $\boldsymbol{d}$ is a possible permanent electric dipole moment induced by the existence of a residual charge and α is the ground state static polarisability. Nevertheless, if the atomic charge q_{Li} does not vanish, the permanent electric dipole moment can be cancelled by an appropriate choice of the spatial origin and we will forget the corresponding energy term.

If $\overline{d}$ is the mean separation between the two trajectories inside the capacitor, the phase shift $\Delta\phi$ induced between the two waves can be written as

$$\Delta\phi = \frac{1}{\hbar} q_{Li} E \overline{d} \frac{L_C}{v} \ . \tag{9}$$

The mean separation between the two trajectories $\overline{d}$ is proportional to diffraction angle θ_d:

$$\overline{d} = \theta_d (z_{out} + z_{in})/2 \tag{10}$$

where z_{in} and z_{out} represent the distances from the first grating to both ends of the capacitor (see figure 1). Then

$$\Delta\phi = \frac{1}{\hbar} q_{Li} E \frac{L_C}{v} \theta_d \frac{z_{out} + z_{in}}{2} \ . \tag{11}$$

To be sensitive to the smallest atomic charge, the interferometer must be designed such as to give the largest possible phase shift. The electric field is obviously limited by the maximum field which can be achieved in the laboratory, but this limit is not very severe: fields as large as $20-30$ MV/m can be achieved in a few millimeters wide gaps [19]. Another condition is that the polarisability energy term should remain small when compared to the atom kinetic energy $mv^2/2$, otherwise the velocity inside the electric field would be markedly modified. Besides an optimization of the geometrical dimensions L_C and $(z_{out} + z_{in})$, the largest gain will be obtained by increasing the kinematic ratio θ_d/v which is given by:

$$\frac{\theta_d}{v} = \frac{h}{mv^2 a}. \tag{12}$$

Because $\Delta\phi \propto 1/v^2$, this expression clearly shows that the sensitivity of the experiment to an atomic charge can be greatly enhanced by the use of a slow atomic beam. For our numerical estimates, we have assumed the following values. The lithium beam mean velocity is $v = 10$ m/s and the grating period a is equal to 335 nm, corresponding to the atomic first resonance line at 671 nm. The resulting first order diffraction angle $\theta_d = 17$ mrad is quite large. The separation between consecutive gratings is equal to $L = 0.6$ m with a capacitor of length $L_C = 0.5$ m located at mid-distance between the first and second gratings so that $(z_{out} + z_{in})/2 = L/2 = 0.3$ m. The applied electric field E is assumed equal to 10^6 V/m, a value for which the polarisability term ($\alpha' = \alpha/4\pi\epsilon_0 = 24.3 \times 10^{-30}$ m^3 [20]) is about 10^{-3} of the atom kinetic energy. With these values, the phase shift is calculated to be:

$$\Delta\phi = q_{Li} \times 2.4 \times 10^{36} \text{ rad.} \tag{13}$$

To reach a limit on the value of $|q_{Li}|$ of the order of $10^{-21} \times |q_e|$ (i.e. the existing limit on $|q_n|$ limit), we must be able to measure a phase shift $\Delta\phi_{min}$ as small as 3.8×10^{-4} rad. The smallest measurable phase shift depends on the signal-to-noise ratio r of the interferometer. If C is the contrast of the signal, N the number of atoms detected per second, t the duration of the measurement and if we observe the linear part of the interference pattern, then

$$r = \frac{\Delta\phi C\sqrt{Nt}}{2}. \tag{14}$$

With a Bragg diffraction interferometer, the theoretical contrast is $C = 100\%$. If the atomic beam is slowed down to 10 m/s and transversely cooled before collimation, the incoming rate can easily reach 10^7 atoms/s. The detection probability can be taken equal to 1 because with realistic values, we estimate possible to detect about 100 fluorescence photons per atom. The smallest measurable phase shift with a signal-to-noise ratio equal to one is then on the order of $6. \times 10^{-4}$ rad/$\sqrt{\text{Hz}}$. An acquisition time on the order of 2 seconds should be enough to detect an atomic charge as small as the present limit on neutron charge, thus establishing the metrological potential of the proposed set-up.

We would now like to focus on some systematic effects that could alter the experiment. It has to be stressed that the present equations assume an exact cancellation of the polarisability term, while this energy term is many orders of magnitude greater than the term due to residual charge. So, special attention should be paid first on the capacitor construction to minimize field gradients, and second, on the symmetry of the design to make the lengths of the two paths inside the capacitor as equal as possible. Finally, the acquisition procedure should be devised to eliminate the systematic effect due to atomic polarisability. This effect depends indeed quadratically on the electric field while an effect due to residual lithium charge would depend linearly on the electric field. One can thus change the polarity of the voltage applied to the capacitor and subtract the value measured with one polarity from the value measured with the opposite polarity. The quadratic part in E will cancel out while the part linear with E will remain. As a consequence, two measurements are requested to get the final limit and the integration time will be four times longer *i.e.* about 8 seconds for a $10^{-21} \times |q_e|$ limit.

In order to get rid of the fringe field of the capacitor, one could work with a pulsed atomic beam and a pulsed voltage on the capacitor, using the scalar Aharonov-Bohm effect. If the voltage is applied when an atomic cloud is completely inside the field region and switched off before any atom has left this region, all atoms are in the electric field for the same amount of time. If the atoms spend a time τ inside the capacitor when the field is applied,

$$\Delta\phi = \frac{1}{\hbar} q_{Li} E \overline{d} \tau\ . \tag{15}$$

If this sequence is repeated with a period equal to T, the net atomic rate is reduced from N to

$$N_p = \frac{t_s}{T} N\ , \tag{16}$$

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if the time t_s during which the source is open is such that $t_s \leq \tau$ (if not, τ must replace t_s in equation 16). To get the best signal-to-noise ratio and the largest phase shift, one must choose τ and t_s as large as possible and T as small as possible. The period T is limited by the entry of the fastest atoms (velocity $v + \Delta v/2$) into the capacitor and the exit of the slowest ones (velocity $v - \Delta v/2$), whereas τ is limited by the entry of the slowest atoms and the exit of the fastest ones. In the best condition, when the atomic beam is chopped just before the first grating, and if the velocity dispersion Δv is small ($\Delta v/v \ll 1$),

$$\tau_{max} = L_C/v - \frac{(z_{in} + z_{out})}{2v}(\Delta v/v) - t_s \;, \tag{17}$$

$$T_{min} = L_C/v + \frac{(z_{in} + z_{out})}{2v}(\Delta v/v) + t_s \;. \tag{18}$$

For a lithium beam slowed down to 10 m/s and cooled down close to the Doppler limit ($\Delta v/v \simeq 0.1$), a capacitor 0.5 m long and for $t_s = \tau_{max}$, then $t_s = 23.5$ ms and T_{min}=76.5 ms. With the parameters already mentioned one could measure a charge q_{Li} as small as the existing limit on the neutron charge q_n in about 16 seconds.

This pulsed mode induces a transient magnetic field that interacts with the magnetic moment of lithium. Thanks to the symmetry of our design, the resulting effect should be equal for both beams and therefore it should cancel out, if we can neglect small symmetry defects. In order to completely cancel this magnetic effect, one can optically pump the lithium atoms in an $m_F = 0$ sublevel which is insensitive to weak magnetic fields. However, this trick is possible only with bosonic ^{7}Li.

Finally, a modification of the present geometry can be considered which gives roughly the same sensitivity to atomic charge but for which the sensitivity to atomic polarisability is hopefully considerably reduced. If, for example, the two arms of the interferometer propagate inside equipotential volumes held at different potentials V_1 and V_2 (see figure 2) during a time τ, the resulting phase shift is simply given by:

$$\Delta\phi = \frac{q_{Li}(V_1 - V_2)\tau}{\hbar}. \tag{19}$$

This expression is very similar to equation (9) where the term $(V_1 - V_2)$ replaces $E\,\overline{d}$. One can hope to produce a phase shift of the same order of magnitude if $(V_1 - V_2) \approx E\,\overline{d}$, while the phase associated to the polarisability term will be considerably reduced. Moreover, if the construction is well symmetric and if the potentials V_1 and V_2 are opposite, with additional entrance and exit electrodes held at $V = 0$, phases associated to the polarisability term should cancel as a result of symmetry. However, these phases are not very easy to evaluate as the electric field is nonzero at the entrance and exit of the equipotential volumes and the geometry of this field is not simple. This arrangement is very nice from a theoretical point of view, but its alignment is more difficult than for the configuration using only one capacitor.

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4 Discussion

A Mach-Zehnder atom interferometer is not the only atom interferometer that could be used. One could also use a Ramsey-Bordé interferometer [12] to test neutrality of atoms. The capacitor should then be set where trajectories are parallel and atoms are in the same internal state in both paths, so that the phase shift depends only on atomic charge. A possible disadvantage of these interferometers is that the observed contrast is around 20 % according to [12] and that many atoms of the source are lost in extra interferometers also present in the apparatus.

In reference [2], S. Chu *et al.* mentioned that their accelerometer, based on a cold atom interferometer and used to measure local acceleration of gravity g, could also be used to measure residual atomic charge. One may think that the method would consist of measuring the acceleration $a_e = q_{A,Z}E/m$ instead of the phase due to the electrostatic potential. If the whole interferometer can be placed inside a homogeneous electric field (this may be an oversimplification as Stark splittings will probably perturb the Raman transitions used as beam splitters), the phase shift due to atom polarisability cancels and the phase shift of the interferometric signal due to the electric field should give a measurement of $q_{A,Z}/m$. Using cesium, this group managed to measure g with a sensitivity of $2 \times 10^{-8} g/\sqrt{\mathrm{Hz}}$ [2,21]. With an electric field $E = 10^6$ V/m, this sensitivity on acceleration leads to a sensitivity on atomic charge of

$$|q_{A,Z}| < 4 \times 2.1 \cdot 10^{-21} q_e/\sqrt{\mathrm{Hz}} \tag{20}$$

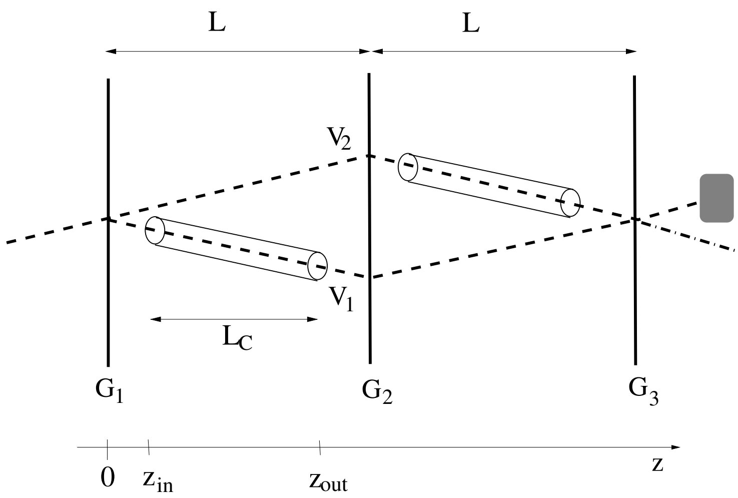

Fig. 2. The same experimental set-up as in figure 1, slightly modified to observe the scalar Aharonov-Bohm effect. The conducting cylinders are held at potentials V_1 and V_2, so that most of propagation occurs in a zero electric field

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where the factor 4 comes from the substraction of two measurements (with and without field). This would thus allow to reach the present limiting value on $|q_n|$ with an acquisition time of about 1 minute.

Finally, as far as we know, the only attempt to measure an electric field induced phase shift with such an interferometer is due to Shimizu, Shimizu and Takuma [22]. The electric field was simply provided by a tinned copper wire. This configuration is however very far from the ones we have considered in the present paper and should provide only a moderate sensitivity.

5 Conclusion

In this paper, we have investigated the possibility to measure, with atom interferometry, a limit on hydrogen atom charge smaller than the existing one. Our experimental proposal is based on a Mach-Zehnder atom interferometer using Bragg diffraction and offers a very good precision in the measurement of residual electric charge of isolated lithium atoms. The main experimental challenge is to obtain a very precise cancellation of the polarisability effect.

An interesting feature of our experimental scheme is that it could also be used for the ^{6}Li isotope. Since the resonance spectra of both isotopes of lithium are not very different, one would only need a small change in the tuning of lasers. Comparison between ^{7}Li and ^{6}Li results would then provide an independent limit on neutron charge.

To derive a limit on $|q_H|$, one is anyway limited by the value of neutron charge. If our limit on residual charge of lithium will be eventually smaller than the existing limit on neutron charge, we should arrive at a limit for $|q_H|$ of about $1.4 \times 10^{-21} \times |q_e|$ (see formulas (1) and (5)) without any particular assumption and of about $2.3 \times 10^{-21} \times |q_e|$ for neutrino charge assuming charge conservation in neutron beta decay.

A direct limit on $|q_H|$ would require an experiment working with hydrogen atoms or molecules. As far as we know, no interferometry with separated arms using an hydrogen beam has been realized up-to-now but such an experiment could be eventually realized using material gratings [23].

6 Acknowledgement

We thank J. Dalibard for his very interesting suggestion about the scalar Aharonov-Bohm effect. We acknowledge financial support from Région Midi-Pyrénées, Université Paul Sabatier (BQR) and IRSAMC.

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