EUROPHYSICS LETTERS 15 January 2002

Europhys. Lett., **57** (2), pp. 158–163 (2002)

Hydrogen atom interferometer with short light pulses

T. HEUPEL[1], M. MEI[1], M. NIERING[1], B. GROSS[1], M. WEITZ[1],
T. W. HÄNSCH[1] and CH. J. BORDÉ[2]

[1] *Max-Planck-Institut für Quantenoptik - 85748 Garching, Germany*
and Sektion Physik der Universität München - 80799 München, Germany
[2] *Laboratoire de Physique des Lasers, UPN - Villetaneuse, France*
and Laboratoire de Radioastronomie Millimetrique, UPMC - Paris, France

(received 25 July 2001; accepted in final form 23 October 2001)

PACS. `03.75.Dg` – Atom and neutron interferometry.
PACS. `39.20.+q` – Atom interferometry techniques.
PACS. `32.80.Lg` – Mechanical effects of light on atoms, molecules, and ions.

Abstract. – We report the realization of a hydrogen atom interferometer experiment using light as the atomic beam splitter. The wave packets of hydrogen atoms excited to the metastable $2S$ state are coherently split up and later recombined with the help of intense nanosecond light pulses. The pulses are generated by a novel phase-coherent source. These experiments can be seen as a step towards a precision measurement of the recoil energy of a hydrogen atom when absorbing a photon and thus of $\hbar/m_{\text{hydrogen}}$.

During the last years, a large number of atom interferometers have been realized [1]. Owing to the small de Broglie wavelength of atoms, these matter wave interferometers can reach a very high sensitivity and gain increasing significance, *e.g.* for precision measurements of rotations [2] or of gravity [3]. Particularly, the determination of the recoil energy shift of an atom when absorbing a photon is of interest since from this an accurate value of $\hbar/m_{\text{atom}}$ can be obtained [4, 5].

In this letter, we report on the realization of an atom interferometer experiment with atomic hydrogen. The experiment is a first step towards a precision measurement of the photon recoil energy of a hydrogen atom [6]. Due to the small mass m_{hyd} of the hydrogen atom, the recoil energy $\hbar\omega_{\text{r}} = \hbar^2 k^2/2m_{\text{hyd}}$ is large. An accurate measurement of the photon recoil energy and thus of $\hbar/m_{\text{hyd}}$ could lead to an improved value of the fine-structure constant α, since the Rydberg constant [7] and the mass ratio of the proton to the electron [8] are precisely known as well as the transition wavelengths involved.

In our experiment, hydrogen atoms are first excited to the metastable $2S$ state. In a second step, the atom interferometer is realized by applying a series of optical pulses tuned to the transition between the metastable $2S$ state and a high-lying P state, in our case to the $15P$ state. The light pulses are generated by a novel phase-coherent source [9] and act as beamsplitters for the atomic de Broglie waves. We use comparatively short (a few ns length) optical pulses in order to address a large velocity class of atoms within the thermal Doppler distribution of the atomic beam. The use of a Rydberg P state ensures a long lifetime of the

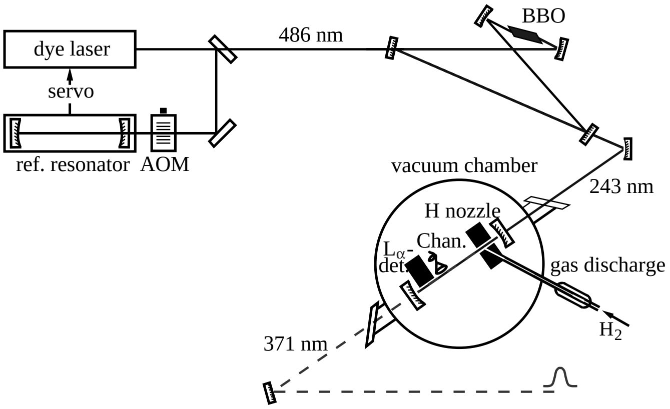

Fig. 1 – Experimental setup for a hydrogen atom interferometer based on a photon echo pulse scheme. (AOM: acousto-optic modulator).

excited P state, thereby reducing unwanted coherence-destroying spontaneous decay during the pulse sequence.

Our interferometer scheme is based on a $\pi/2$-π-$\pi/2$ pulse sequence ("photon echo" sequence); see ref. [10] for a discussion of the connection between photon echo experiments and atomic interferometry. We use a light pulse technique [3,5] to realize this sequence. The light pulses drive Rabi oscillations between the metastable $2S$ state and the Rydberg $15P$ state. For the sake of simplicity, let us assume that we are dealing with a two-level system. The effects of the atom light interactions in the $\pi/2$-π-$\pi/2$ pulse sequence are determined from conservation of momentum. If the momentum of an atom is such that the atom is in resonance with the light field, the first $\pi/2$ pulse acts as a beam splitter, introducing a velocity difference $\boldsymbol{v}_r = \hbar\boldsymbol{k}/m$ between the two states. After a time T, the π pulse acts as a mirror and redirects the wave packets so that they overlap at the time $2T$ of the second $\pi/2$ pulse which closes the interferometer and causes the two wave packets to interfere (for a more detailed description the $\pi/2$-π-$\pi/2$ pulse sequence, see also [1]). By changing the optical phase of the final $\pi/2$ pulse, we are able to observe a sinusoidal interference pattern in the number of atoms left in the excited $15P$ state.

The experimental setup for the hydrogen atom interferometer is schematically depicted in fig. 1. The experiment consists of two main steps. 1) Hydrogen atoms initially in the $1S$ ground state are excited to the metastable $2S$ state. 2) The interferometer pulse sequence is applied. The hydrogen $1S$-$2S$ spectrometer to realize the first part has been described in detail previously [11]. Briefly, the $1S$-$2S$ transition is driven in a cold atomic beam by Doppler-free two-photon excitation ($1S$, $F = 1$, $m_\mathrm{F} = \pm 1 \rightarrow 2S$, $F = 1$, $m_\mathrm{F} = \pm 1$). The radiation of an ultra-stable dye laser at 486 nm is frequency doubled and the UV radiation at 243 nm is resonantly enhanced in a linear cavity inside the vacuum chamber to excite the atoms into the $2S$ state. Atoms in the $2S$ state can be probed by an electric quenching field forcing the emission of Lyman-α radiation which is detected by a solar-blind photomultiplier tube. A mechanical chopper is used to switch the light field periodically on and off. The photomultiplier signal is read only at dark times such that background counts caused by the excitation light field at 243 nm are suppressed (the total flux rate is on the order of 10^{10} atoms/s for the 7 K thermal velocity distribution of the hydrogen nozzle). In addition, the chopper allows time-resolved photon counting and therefore the selection of slow atoms from the thermal velocity distribution.

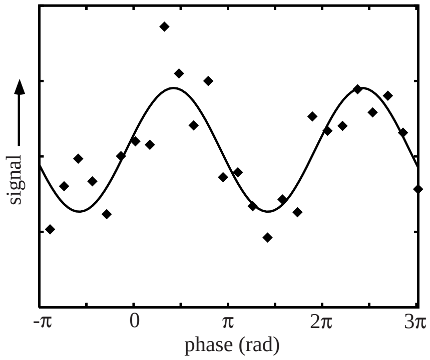

Fig. 2 – Typical experimental fringe signal for a hydrogen atom interferometer recorded with a photon echo pulse scheme. The plot gives the difference of $15P$-$1S$ fluorescence signal, as measured with a lock-in amplifier, as a function of the optical phase of the final pulse.

In the second step the $\pi/2$-π-$\pi/2$ interferometer sequence of light pulses is applied. The source for the generation of the short, powerful, phase-coherent light pulses has been described in detail previously [9]. Briefly, light from a cw Ti:Sapphire laser at 742 nm is coupled into a high-finesse cavity where it is enhanced by a factor of about 1500. The frequency of the cw Ti:Sapphire laser is stabilized to a molecular iodine line using Doppler-free frequency modulation spectroscopy in a cell [12]. Inside the resonator, an acousto-optic modulator (AOM) acts as a fast optical switch. By applying a RF pulse to the AOM, a large amount of the stored and enhanced power is coupled out into a short, powerful light pulse. A well-polished etalon inserted in the long arm of the resonator is used to suppress cavity-enhanced stimulated Brillouin scattering [13]. After single-pass frequency doubling using a $LiIO_3$ crystal, the light pulses are resonant with the $2S$-$15P$ transition of atomic hydrogen. The peak power of the optical pulses at 371 nm was 2 to 5 W typically.

We generate the $\pi/2$-π-$\pi/2$ sequence of light pulses by carefully adjusting the power levels of the RF pulses driving the intra-cavity AOM. The three light pulses, each 13 ns long and separated by 100 ns, are matched to a beam waist of $2\omega_0 \sim 600\,\mu$m in the center of the hydrogen vacuum chamber, which is slightly bigger than the beam waist of the $1S$-$2S$ excitation beam. The finite lifetime of the $15P$ state (roughly 650 ns) restricts the possible drift time between the interferometer pulses to comparatively short times.

The interferometer pulse sequence was typically applied with a delay of $600\,\mu$s after the $1S$-$2S$ excitation light had been extinguished. In this way, slow atoms (velocities less than 160 m/s) from the thermal velocity distribution were selected.

For the detection of atoms in the $15P$ state after the interferometer pulse sequence is completed, we use a cesium-iodide–coated channeltron detector. Atoms in the $15P$ state decay with 80% probability to the $1S$ ground state, thereby emitting a photon at 91.6 nm. We detect the fluorescence in a $5\,\mu$s time interval directly after the final interferometer pulse as a function of the phase of this pulse. A RF phase shifter at 20 MHz is used to shift the phase of the final RF pulse driving the intra-cavity AOM, which directly transfers to the optical phase of the light pulse. The fluorescence signals are recorded with two independent photon counters. The chopper frequency, which at the same time is the repetition rate of the experiment, is 285 Hz. The used integration time for each data point is 2 s.

Figure 2 shows an observed interferometer signal with sinusoidal fringes, as expected. For this plot, 10 single spectra were averaged over the shown phase region. A sine function is fitted to the data points with a periodicity of $1.001(50) \cdot 2\pi$.

The observed contrast $V = (S_{\max} - S_{\min})/(S_{\max} + S_{\min})$, which quanitifies the extent to which the interference pattern with the maximum and minimum count rates $S_{\max}$ and $S_{\min}$ is experimentally observable, was typically 10% in these initial experiments. Theoretically, in the limit of the Doppler width of the atoms being much larger than the frequency bandwidth of the optical pulses, one expects a maximum achievable contrast of 27% for the used photon-echo pulse sequence [3]. We attribute the reduced experimental contrast mainly to the fact that at present we simultaneoulsly excite transitions to several upper-state fine-structure and hyperfine components with different line strengths. This difficulty could be avoided by initially selecting atoms in, *e.g.*, the $m_{\mathrm{F}} = 1$ Zeeman state and driving only the transition $F = 1$, $m_{\mathrm{F}} = 1 \rightarrow F' = 2$, $m_{\mathrm{F'}} = 2$ with circularly polarized light. In addition, stray electric fields can also reduce the fringe contrast. The present interferometer experiment was performed relatively close to the channeltron detector used for monitoring the fluorescence signal from atoms in the $15P$ state. Finally, the finite lifetime of the $15P$ state also somewhat reduces the contrast, since it is only a factor of three above the total length of the interferometer pulse sequence. The observed interferometer signal does not show the expected minimum at zero additional phase shift of the final pulse. The phase shift is attributed to electric stray fields. In a two-level scheme, the used $\pi/2$-π-$\pi/2$ interferometer pulse sequence is insensititive to energy shifts which are homogenous in time or space and only yields a (small) fringe shift in the presence of field gradients. When there are more involved levels, one in addition expects a certain sensitivity to homogeneous electric fields. In the future, these problems can be avoided by detecting the population left in the metastable $2S$ state after the interferometer sequence. Signal detection then could occur spatially or temporally separated from the atom interferometer sequence if desired.

In order to measure the recoil energy shift $\hbar\omega_{\mathrm{rec}}$ of a hydrogen atom when absorbing a photon ($\hbar\omega_{\mathrm{rec}} = (\hbar k)^2/2m_{\mathrm{hyd}}$), the atom interferometer scheme should be extended to a more sophisticated pulse sequence. Since the transition wavelengths involved are known precisely, the recoil energy shift directly leads to a measurement of h/m_{hyd}. This represents a way towards expressing atomic mass in terms of frequency. On the other hand, together with the well-known Rydberg constant R_∞ and the mass ratio of the hydrogen atom to the electron, it is possible to deduce the fine-structure constant α by $\alpha^2 = (2R_\infty/c) \cdot h/m_{\mathrm{e}}$ from such an experiment (m_{e} being the mass of the electron and c being the speed of light). Similar experiments have so far been carried out only with heavier atoms, which give a smaller recoil shift [4, 14]. Note that in this way it is possible to obtain a value which is independent of QED calculations. In contrast, the currently most precise value of α is deduced from a comparison of the experimental value and theoretical prediction of $(g_{\mathrm{e}} - 2)$ [15] and therefore QED dependent.

For the realization of the hydrogen atom interferometer experiment to measure the recoil energy shift, it seems most reasonable to use a Doppler-free two-photon Ramsey excitation scheme on the $1S$-$2S$ transitions with additional light pulses driving transitions from the $2S$ state to a high-lying Rydberg P state. The proposed scheme is shown in fig. 3; see also the earlier work of Bordé, Weitz and Hänsch [6]. In the first Ramsey excitation zone a coherent superposition of the $1S$ ground state and the metastable $2S$ state is created. The part of the wave packet in the $2S$ state is deflected and later redirected by pairs of counterpropagating π pulses driving stimulated transitions to the high-lying P state and back to the $2S$ state. In this way, the limitations due to the finite lifetime of the excited P state are eliminated. Since the pulses for absorption and stimulated emission of photons are counterpropagating, two photon momenta per pulse pair are transferred to the atom, leading to a larger separation of the atomic paths. On the other hand, the part of the hydrogen atomic wavepacket in the

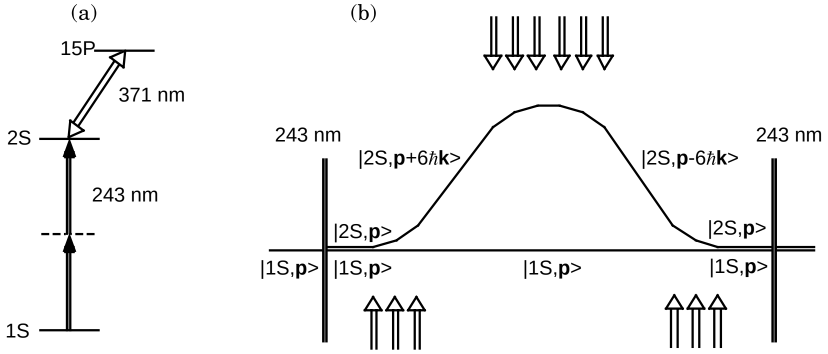

Fig. 3 – (a) Level scheme and (b) recoil diagram of the proposed hydrogen atom interferometer for measurement of the photon recoil energy $\hbar\omega_{\mathrm{rec}}$. A coherent superposition of the states $1S$ and $2S$ is generated by Doppler-free two-photon excitation in a standing wave near 243 nm. The path in the $2S$ state is then bent out with a sequence of π pulse pairs, each of which are performed with two counterpropagating laser pulses inducing transitions $2S$-nP and nP-$2S$ (*e.g.*, $n = 15$), respectively. For the sake of simplicity, only the propagation direction of the first pulse of the pair, which leaves the atom in the nP state, is shown (double arrows). Shortly afterwards, a counterpropagating laser pulse then stimulates the atom back into the $2S$ state. Each of the pulse pairs transfers $2\hbar k$ momentum to the atom. Finally, the atom interferometer is closed by Doppler-free two-photon excitation in a second interaction with a 243 nm standing wave. For better visualisation, the interferometer is shown with the pulse pairs transferring photon momenta directed transversely to the initial atomic velocity. For practical reasons, the use of a longitudial configuration may seem preferable experimentally.

$1S$ state is not affected by the light pulses and serves as a phase reference. By using an appropriate pulse sequence for the π pulses, the part of the atomic wave packet in the $2S$ state is later overlapped again with the path in the $1S$ state, and the second Ramsey zone closes the interferometer.

The fringe signal is most easily observed by monitoring the population in the $2S$ state after the interferometer pulse sequence. This can be achieved by either applying a dc field to force the emission of a Lyman-alpha photon or by applying a pulse tuned to $2S$-nP, in which case the atom spontaneously decays to the $1S$ ground state and subsequent collection of the emitted photons. The recoil energy of the hydrogen atom can be deduced by comparing the fringe pattern of the atom interferometer to that recorded with a simple $1S$-$2S$ Ramsey scheme with no applied pulses tuned to $2S$-nP. The recoil energy shift for a pair of counterpropagating π pulses at a wavelength of 371 nm is 5.8 MHz. Note that the phase shift to be measured scales quadratically with the number of light pulses used to deflect the $2S$ arm of the interferometer [6].

A two-photon Ramsey excitation with atomic hydrogen has recently been observed in our group both with spatially separated Ramsey zones [16] and with pulses in the time domain [17]. In these preliminary experiments, the observed linewidth was typically a few kHz. When using $10\,\pi$ pulses for deflecting and later redirecting the interferometer arms, estimates show that a precision for a determination of the fine-structure constant at the level of 10^{-9} should in principle be possible, if we assume that a fringe with 1 kHz period can be split to one part in 10^3. Nevertheless, such an experiment at present seems technically difficult with a liquid-helium–cooled hydrogen atomic beam, as used in these preliminary experiments since the available interaction times at realistic optical intensities then only allow for small pulse areas on the weak $1S$-$2S$ two-photon transition. On the other hand, recent progress in magnetically trapped atomic hydrogen, which can be evaporatively cooled down to the microkelvin regime [18], makes this light atom a very promising candidate for precision measurements of the photon recoil. Finally, the presently used "photon-echo" atom interferometer has a geometry sensitive to the Earth's acceleration g and could be used when testing for a possible difference in g for hydrogen and antihydrogen. We wish to point out that in contrast to atom interferometric schemes relying on scattering from material gratings, the use of light as a beamsplitter is feasible both for matter and antimatter wave packets.

In summary, we have realized the first hydrogen atom interferometer making use of light pulse interferometer techniques to split and later redirect the atomic paths. This is a first step towards the realization of a hydrogen atom interferometer experiment for measuring the recoil energy shift of the hydrogen atom when absorbing a photon. With the geometry of fig. 3, a precise determination of $\hbar/m_{\mathrm{hyd}}$ and of the fine-structure constant α seems possible.

REFERENCES

[1] For an overview, see articles in BERMAN P. (Editor), *Atom Interferometry* (Academic Press, San Diego) 1997.

[2] GUSTAVSON T. L., LANDRAGIN A. and KASEVICH M. A., *Class. Quantum. Grav.*, **17** (2000) 2385.

[3] PETERS A., CHUNG K. Y. and CHU S., to be published in *Metrologia*, **38** (2001).

[4] HALL J. L., BORDÉ CH. J. and UEHARA K., *Phys. Rev. Lett.*, **37** (1976) 1339.

[5] YOUNG B., KASEVICH M. and CHU S., in ref. [1], p. 363.

[6] BORDÉ CH. J., WEITZ M. and HÄNSCH T. W., in *Laser Spectroscopy XI*, edited by BLOOMFIELD L., GALLAGHER T. and LARSON D. (AIP, New York) 1994, p. 76.

[7] UDEM TH., HUBER A., GROSS B., REICHERT J., PREVEDELLI M., WEITZ M. and HÄNSCH T. W., *Phys. Rev. Lett.*, **79** (1997) 2646.

[8] FARNHAM D. L., VAN DYCK R. S. jr. and SCHWINBERG B. P., *Phys. Rev. Lett.*, **75** (1995) 3598.

[9] HEUPEL T., WEITZ M. and HÄNSCH T. W., *Opt. Lett.*, **22** (1997) 1719.

[10] BORDÉ CH. J. *et al.*, *Phys. Rev. A*, **30** (1984) 1836; BORDÉ CH. J., in *Laser Spectroscopy X*, edited by DUCLOY M., GIACOBINO E. and CAMY G. (World Scientific, Singapore) 1992, p. 239.

[11] HUBER A., UDEM TH., GROSS B., REICHERT J., KOUROGI M., PACHUCKI K., WEITZ M. and HÄNSCH T. W., *Phys. Rev. Lett.*, **80** (1998) 468.

[12] HALL J. L., HOLLBERG L., BAER T. and ROBINSON H. G., *Appl. Phys. Lett.*, **39** (1981) 680; CAMY G., BORDÉ CH. J. and DUCLOY M., *Opt. Commun.*, **41** (1982) 325 and references therein.

[13] HEUPEL T., WEITZ M., CHU S. and HÄNSCH T. W., *Opt. Commun.*, **140** (1997) 281.

[14] WEISS D. S., YOUNG B. C. and CHU S., *Phys. Rev. Lett.*, **70** (1993) 2706.

[15] KINOSHITA T., *Rep. Prog. Phys.*, **59** (1996) 1459 and references therein.

[16] HUBER A., GROSS B., WEITZ M. and HÄNSCH T. W., *Phys. Rev. A*, **58** (1998) R2631.

[17] GROSS B., HUBER A., NIERING M., WEITZ M. and HÄNSCH T. W., *Europhys. Lett.*, **44** (1998) 186.

[18] FRIED D. G. *et al.*, *Phys. Rev. Lett.*, **81** (1998) 3811.