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# PHYSICAL REVIEW A

## ATOMIC, MOLECULAR, AND OPTICAL PHYSICS

THIRD SERIES, VOLUME 51, NUMBER 6 JUNE 1995

## RAPID COMMUNICATIONS

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# Measurement of the Aharonov-Casher phase of aligned Rb atoms

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(Received 7 November 1994)

We have investigated the phase shift caused by a static electric field on a beam of Rb atoms carrying alignment (but no orientation) using an all optical technique with spatially separated pump and probe regions. Quantitative measurements of the phase shift agree with theoretical predictions to within 1.4%. An experimental demonstration of the velocity independence of the effect based on time-resolved measurements is given.

PACS number(s): 03.65.Bz, 12.20.Fv

The Aharonov-Casher (AC) phase $\Phi_{AC}$ accumulated by a particle carrying a magnetic moment $\vec{\mu}$ upon traversing a closed path $(C)$ around a charged wire [Fig. 1(a)] is given (in *Système International* units) by

$$\Phi_{AC}=\frac{1}{\hbar c^2}\oint_{(C)}\vec{\mu}\times\vec{E}(\vec{s})\cdot d\vec{s}, \tag{1}$$

where $\vec{E}(\vec{s})$ is the electric field along the trajectory [1]. The AC phase is independent of the shape of the trajectory. The topological nature of the effect implies furthermore that it is nondispersive, i.e., that its magnitude does not depend on the particle velocity.

The AC phase can be measured in a two-beam interferometric experiment, in which both beams experience phase shifts $\pm\Phi_{AC}/2$ [Fig. 1(b)]. It has been pointed out by Anandan [2] and Casella [3] that for straight-line trajectories an equivalent phase shift should arise when each of the interferometer arms traverses a region of constant electric field [Fig. 1(c)]. An experiment of this kind has been performed with a neutron interferometer [4]. With an experimental accuracy of 16%, the obtained result deviated, however, by almost two standard deviations from the prediction of Eq. (1). An alternative method to measure $\Phi_{AC}$ is one in which the interferometer arms are distinguished (labeled) not by external degrees of freedom (trajectories), but by internal degrees of freedom such as principal or magnetic quantum numbers [Fig. 1(d)]. While the former labeling has been applied to measure $\Phi_{AC}$ in an optical Ramsey experiment [5] on Ca atoms, the latter was first applied by Sangster *et al.* [6] using an rf-Ramsey technique on TlF. In that experiment $\Delta m=1$ spin coherence was used to measure the AC phase shift of fluorine *nuclear magnetic moments* $(I=\frac{1}{2})$. The results agreed with the prediction from Eq. (1) within 4%; an improved version of that experiment was recently completed [7].

The use of internal spin labeling avoids the technically demanding implementation of a split-beam interferometer, but requires the two arms to be in different internal angular-momentum states with a well-defined relative phase [Fig. 1(e)].

In the present paper we report the measurement of a *purely atomic* AC phase shift performed on the ground state of $^{85}$Rb prepared in the $F=3$ hyperfine state. Different features are the use of $\Delta m=2$ spin coherence and a purely optical preparation and detection. We furthermore demonstrate the linear field dependence of the phase shift and verify its nondispersive character.

Our experiment was performed on a thermal Rb atomic beam using spatially separated pump and probe regions (Faraday-Ramsey spectroscopy). This apparatus has proven in the past to be an extremely sensitive tool for the measurement of small phase shifts $\Delta\Phi$ induced by the interaction of magnetic moments with static magnetic fields yielding sensitivities $\Delta\Phi\approx 400$ $\mu$rad Hz$^{-1/2}$ [8]. We start by discussing the principle of the experiment. The atomic beam, traveling in the $\hat{x}$ direction (Fig. 2), is first optically pumped by a linearly polarized $(\hat{e}=\hat{y})$ beam from a single-mode diode

 

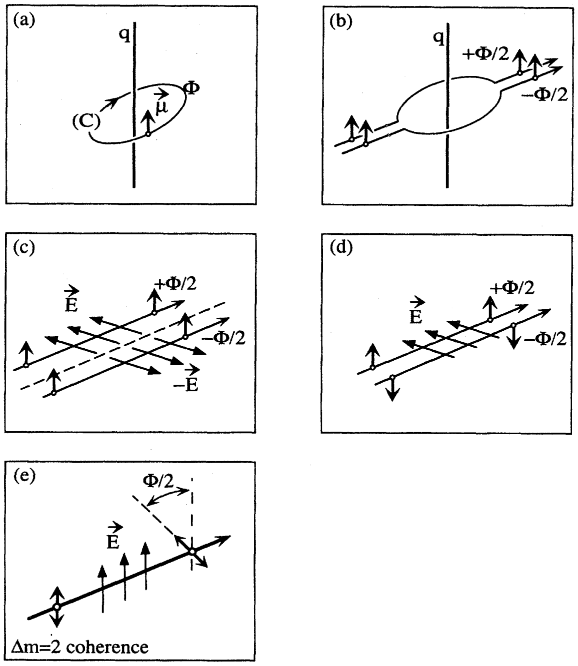


FIG. 1. Variants of the Aharonov-Casher effect: (a) original proposal; (b) interferometric scheme to detect the effect; (c) topological variant of (b) with rectilinear trajectories and homogeneous fields; (d) same as (c) with simultaneous reversal of $\mu$ and $E$ in one interferometer arm; (e) present experiment, spatial coherence replaced by spin coherence.

laser tuned to the center of the resolved $F=3 \rightarrow F'=4$ hyperfine component of the $D_2$ line of $^{85}$Rb. By optical pumping with linearly polarized light populations are redistributed among the magnetic sublevels of the ground state and an alignment ($\Delta m=2$) coherence builds up. The anisotropy connected with the induced alignment corresponds to that of a uniaxial birefringence [9]. Upon exposure to a static, homogeneous magnetic field $B_Z$ for a time $T$, the Zeeman components $|F,M_F\rangle$ acquire phase factors $\exp(iM_F\omega_L T)$, where $\omega_L=g_F\mu_B B_Z/\hbar$ is the Larmor frequency. The $\Delta m=2$ coherences, i.e., of the coherent superposition of states $|F,M_F\rangle$ and $|F,M_F\pm 2\rangle$ thus acquire phases $\exp(\pm 2i\omega_L T)$, which can be shown to be equivalent to a

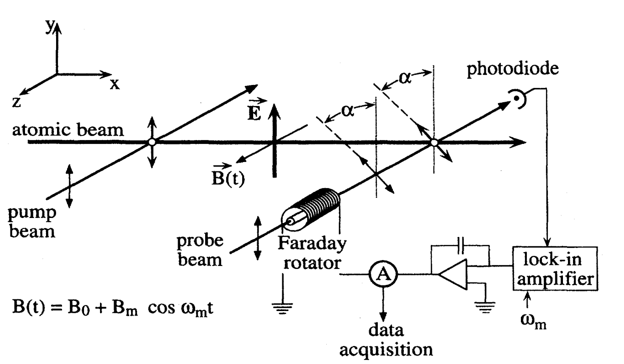


FIG. 2. Experimental setup for the quantitative measurement of the AC phase shift. Details are discussed in the text.

precession of the alignment in the $x$-$y$ plane by an angle $\alpha=\Phi_L=\omega_L T$ [9]. After the time $T$, i.e., a distance $L=vT$ downstream from the pump region, the atomic ground-state coherence is probed by the forward scattering of a weak probe beam polarized parallel to the pump beam. The intensity as well as the polarization of the probe beam are altered by the presence of ground-state coherence in the probe region, so that two complementary types of measurements may be performed. One can measure the $B$-field dependence of either the transmitted intensity $I_t$ or the orientation $\Phi_F$ of the major axis of its elliptical polarization. The former experiment may be interpreted as a pump-probe generalization of dark resonance spectroscopy [10], while the latter is an extension of the well-known single-beam nonlinear Faraday effect [9]. We have shown previously [8,9] that for a sufficiently weak probe beam, which induces less than one optical pumping cycle during the atomic transit time, the signals in both experiments may be expressed as

$$I_t \propto \langle \cos 2\alpha \rangle_v \tag{2a}$$

and

$$\Phi_F \propto \langle \sin 2\alpha \rangle_v . \tag{2b}$$

$\alpha$ is the angle between the probe beam polarization and the orientation of the alignment in the probe region, and is given by $\alpha=\Phi_L$ when a magnetic field only is applied in the interaction region. $\langle \ \rangle_v$ denotes the average over the Maxwellian velocity distribution. The proportionality factor contains the alignment produced in the pump region.

The measurement of the velocity averaged AC phase shift reported here is based on the signal $I_t$. This signal avoids experimental problems associated with polarization spectroscopy, such as imperfect polarizers, window birefringence, or temperature-dependent polarization birefringence in the polarization modulator. A dispersive-shaped signal is generated by applying a small-amplitude modulation to the magnetic field and performing a phase-sensitive detection of $I_t$. The line shape is then given by

$$S(\alpha) \propto \frac{dI_t}{dB} \propto \left\langle \frac{1}{v} \sin 2\alpha \right\rangle_v , \tag{3}$$

which represents a dispersive-shaped Ramsey fringe pattern centered around $\alpha=0$.

Following the analysis presented in Fig. 1 the precession angle of the alignment in the case of crossed $E$ and $B$ fields (Fig. 2) is given by $\alpha=\Phi_L+\Phi_{AC}/2$. We measure $\alpha$ by using a feedback technique that keeps the plane of polarization of the probe beam parallel to the alignment in the probe region. The error signal of the feedback loop, i.e., the current through the Faraday rotator (Fig. 2), is thus proportional to $\alpha$ and may be easily calibrated. With this setup we measured $\Phi_{AC}$ for a set of five values of $E$ in the range 0–6.8 kV/cm (see inset of Fig. 3). The applied magnetic field in these measurements was adjusted to compensate for any residual fields, assuring that $\Phi_L=0$, so that $\alpha=\Phi_{AC}/2$. For each run the slope of the dependence of $\Phi_{AC}$ on $E$ was determined by a least-squares fit and represented a data point in Fig. 3. The various data points were taken in different runs after realigning the apparatus and demagnetizing the $\mu$-metal magnetic

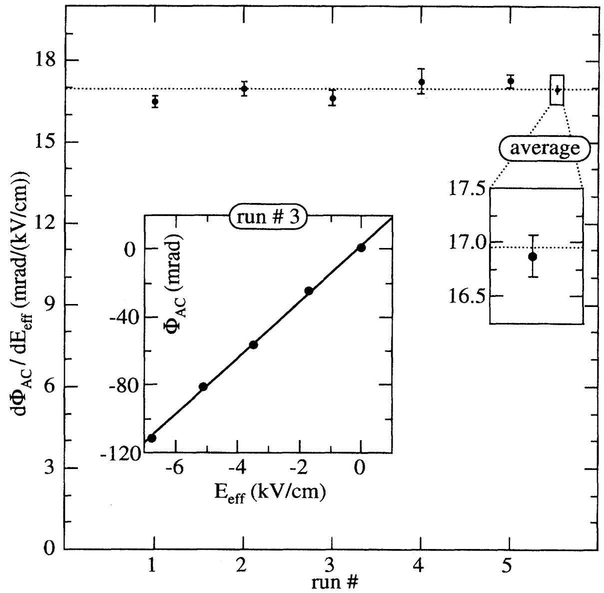


FIG. 3. Independent measurements of the slope $d\Phi_{\rm AC}/dE$. The dotted line represents the theoretical prediction from Eq. (1). Inset: linear dependence of $\Phi_{\rm AC}$ on the strength of the electric field; the statistical errors are of the size of the data points.

shields. The error bars are statistical errors from the linear fits. The data points give consistent results with an average value of

$$\frac{d\Phi_{\rm AC}}{dE}=16.85(19)(15)\ \ \text{mrad/(kV/cm)},$$

where the first error is a statistical $(1\sigma)$ error, and the second error represents a systematic uncertainty in our knowledge of the electric field.

The field was produced by a set of rectangular electrodes ($26\times5$ cm$^2$) separated by 9 mm. The voltage was applied to one electrode, while the other was grounded. This arrangement was located symmetrically between the pump and probe regions separated by 30 cm. Furthermore, two grounded circular diaphragms were introduced between the laser beams and the electrodes proper. The effect of electric fringe fields and the boundary conditions imposed by the diaphragms was evaluated numerically. The second error in the above result reflects the uncertainty in this procedure. The theoretical prediction of the phase shift based on Eq. (1) with $\mu/h=g_F\mu_B/h=467$ kHz/G is $d\Phi_{\rm AC}/dE=16.96$ mrad/(kV/cm) and is in good agreement with the measured value.

We next address the nondispersive nature of the AC phase shift. The velocity independence becomes evident when one considers that the AC phase shift may also be interpreted (to lowest order in the atom velocity $v$) in terms of the motional $B$ field $\vec{B}_{\rm mot}=-(\vec{v}/c^2)\times\vec{E}$ [1,4,6] experienced by the atom in its rest frame. Faster atoms "see" a stronger field $\vec{B}_{\rm mot}$, but are exposed to it for a shorter time and vice versa. In order to verify this prediction we performed a time-resolved experiment, in which coherence was produced by pulsing the pump beam and detecting the orientation of the alignment as a function of the time following this pulse. The limited bandwidth of the feedback loop used in the experiment described above prevented us from using the dark resonance technique. We therefore measured the time-dependent Faraday rotation angle $\Phi_F$ [Eq. (2b)] by analyzing the transmitted probe polarization with a 45° polarizer. In this experiment a small magnetic field (typically 4 to 5 mG) was applied in order to produce a velocity and hence time-dependent orientation of the alignment. The typical shape of the resulting transient Faraday rotation in the presence of electric fields $\pm E$ is then given by

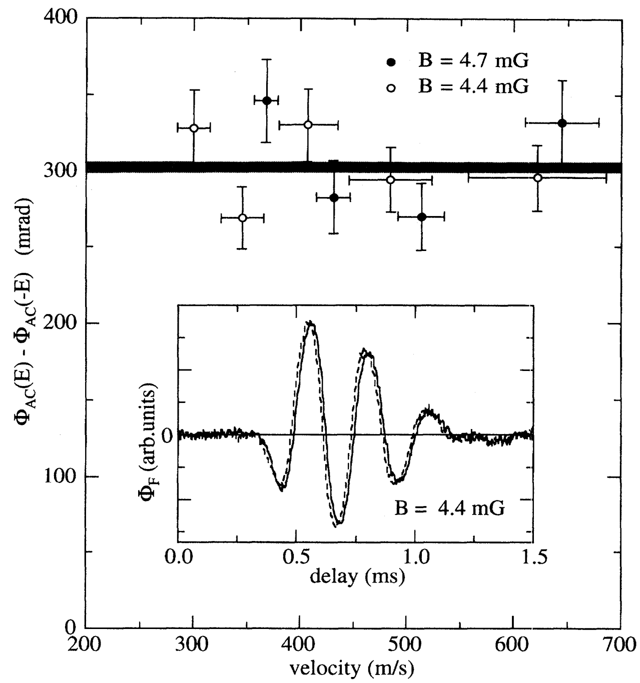


FIG. 4. Experimental verification of the nondispersive character of the AC phase shift in crossed $E$ ($\pm8.88$ kV/cm) and $B$ fields. Data points are $E$-field reversal-induced phase shifts at the zero crossings of the transient Faraday rotation (see inset) following a pulsed excitation of coherence. Vertical bars are statistical errors; horizontal bars represent the velocity spread due to the finite pulse width.

$$\Phi_F(t)dt\propto\rho(t)\sin[2\omega_Lt\pm\Phi_{\rm AC}(|E|)]dt, \tag{4}$$

where $\rho(t)dt$ is the atomic density "seen" by the probe laser in the interval $[t,t+dt]$. Typical line shapes for $B=4.4$ mG and $E=\pm8.88$ kV/cm are shown as an inset of Fig. 4. From Eq. (4) one sees that $\Phi_{\rm AC}$ appears as a phase shift in the transient signal. It can hence be extracted by measuring the electric-field-induced shifts of the zero crossings of the oscillatory structure. Since the delay time between the pulsed preparation of the alignment and the detection of a specific zero crossing corresponds to a well-defined velocity of the probed atoms, $\Phi_{\rm AC}$ can thus be measured for a set of distinct velocities. By repeating the same experiment with $B=4.7$ mG we used the dependence of the positions of the zero crossings on the magnetic field to obtain $\Phi_{\rm AC}$ for an additional set of velocities. The results are shown in Fig. 4 as open and filled data points. Within the experimental uncertainties, the AC phase shift is independent of the atomic velocity in the range 300–650 m/s and its average value is in good agreement with the prediction from Eq. (1) shown as a shaded bar.

In this work we have reported an experimental observation of the Aharonov-Casher effect in an atomic system. This is illustrated in Fig. 5, where we compare the results of measurements of the Aharonov-Casher phase in different systems (neutron, TlF, Ca, and Rb). Our results represent the most precise measurement of the AC phase shift in any system. The original discussion of the AC phase shift [1] was based on a particle carrying a vector magnetization ($\langle\vec{\mu}\rangle\neq 0$). In our experiment the atoms carried no spin polarization ($\langle\vec{\mu}\rangle=0$), but rather an alignment (tensor polarization). Although no formal theory of the AC phase shift in the case of aligned particles ($\Delta m=2$ spin coherences) has been presented so far, our analysis directly connects our observations to the expression originally proposed by Aharonov and Casher.

*Noted added.* After completion of this work, we became aware of another measurement of the AC phase in an atomic system [5].

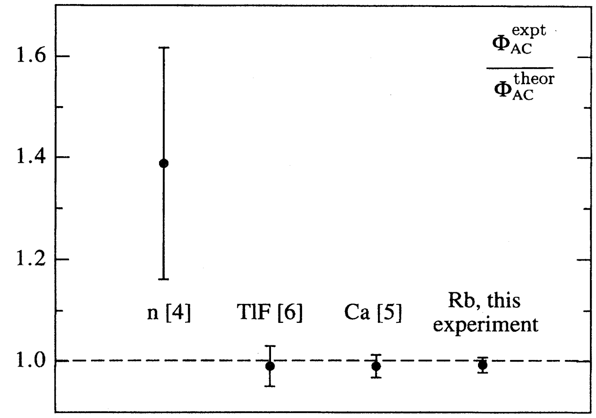


FIG. 5. Comparison of experimental tests of the Aharonov-Casher effect.

The authors acknowledge T. W. Hänsch and S. I. Kanorsky for their constant interest in this work and for many stimulating discussions, and S. B. Ross and T. Udem for a critical reading of the manuscript. We also thank J. Helmcke for communicating the results of the PTB team prior to publication.

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