Measurement of Parity Nonconservation in Atomic Cesium

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A new measurement of parity nonconservation in cesium is reported. The experimental technique involves measurement of the $6S \rightarrow 7S$ transition rate by use of crossed atomic and laser beams in a region of perpendicular electric and magnetic fields. Our results are $\mathrm{Im}\mathscr{E}_{\mathrm{PNC}}/\beta = -1.65 \pm 0.13$ mV/cm and $C_{2p} = -2 \pm 2$. These results are in agreement with previous measurements in cesium and the predictions of the electroweak standard model. This experimental technique will allow future measurements of significantly higher precision.

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The standard model for the electroweak interaction predicts a parity-nonconserving (PNC) neutral-current interaction between electrons and nucleons. In 1974 the Bouchiats[1] proposed that this effect might be observable in large-Z atoms, thus generating a decade of experimental effort. Measurements of PNC have now been made in bismuth and lead by observation of the optical rotation of light,[2] and in thallium[3,4] and cesium[5] by use of the technique of Stark interference. Here we report a new measurement of parity nonconservation in cesium which is more precise than the previous measurements in atoms and is approaching the precision of the best high-energy test of the electroweak theory. This result is in good agreement with previous measurements in cesium. By comparing the PNC observed on two different hyperfine transitions we also set a much lower limit for the proton-axial-vector PNC contribution.

Parity-nonconservation measurements in atoms are valuable because they test the electroweak theory in a different regime from that probed by high-energy experiments. As well as being sensitive to a very different energy scale for the exchange of virtual particles, atomic experiments also involve a nearly orthogonal set of electron-quark couplings. Because of this, atomic PNC measurements, when combined with high-energy results, can provide useful tests of the electroweak radiative corrections and alternatives to the standard model.

Deriving information about the basic neutral-current interaction from atomic PNC measurements requires knowledge of the atomic wave functions. Cesium is a particularly good atom in this respect because of its single-electron character. This enables a more direct and accurate calculation of the wave function than is possible for other heavy atoms.

The basic experimental concept has been discussed previously[6] but we will review the essential points. The PNC interaction in an atom mixes the S and P eigenstates, allowing a small electric dipole ($E1$) transition amplitude between states of the same parity. In all atomic PNC experiments, this parity-nonconserving amplitude (A_{PNC}) is measured by observation of its interference with a much larger parity-conserving amplitude. In our experiment, the parity-conserving amplitude is a "Stark-induced" $E1$ amplitude (A_{St}) created by the application of a dc electric field to mix S and P states. The early Stark interference experiments[3,5] measured the spin polarization of the excited state due to this PNC interference. In our experiment, we are able to observe the interference directly in the transition rate by applying a magnetic field to break the degeneracy of the Zeeman levels. The idea of using electric and magnetic fields was proposed by a number of authors[7] and used in the recent thallium PNC measurement of Drell and Commins.[4] A similar technique was also demonstrated in our measurement[6] of the Cs $6S \rightarrow 7S$ magnetic dipole amplitude (A_{M1}). A unique feature of our approach is the use of crossed laser and atomic beams. This yields narrow transition linewidths which have the important experimental advantage of allowing the use of a small (<100 G) magnetic field. Other desirable features of an atomic-beam experiment include the reduction of collisions, radiation trapping, and molecular backgrounds.

We measure the PNC interference term on both the $6S_{F=4} \rightarrow 7S_{F'=3}$ and $6S_{F=3} \rightarrow 7S_{F'=4}$ hyperfine lines shown in Fig. 1. The basic field configuration for the experiment is shown in Fig. 2. A standing-wave laser beam along the $\hat{\mathbf{y}}$ axis excites transitions in a region with an electric field ($\mathbf{E}$) in the $\hat{\mathbf{x}}$ direction and a magnetic field ($\mathbf{B}$) along the $\hat{\mathbf{z}}$ axis. The laser field has polarization $\boldsymbol{\epsilon} = \epsilon_z \hat{\mathbf{z}} + i\epsilon_x \hat{\mathbf{x}}$, where ϵ_x and ϵ_z are real. For any transition between particular Zeeman sublevels (m and m') the transition probability is

$$I = |A_{\mathrm{St}} + A_{M1} + A_{\mathrm{PNC}}|^2, \tag{1}$$

where each A is a function of F, F', m, and m'. Using the results of Gilbert[8] we substitute for the amplitudes in Eq. (1) and obtain for $F \neq F'$,

$$I_{Fm}^{F'm'} = [\beta^2 E^2 \epsilon_z^2 \mp 2\beta E \epsilon_z \,\mathrm{Im}\mathscr{E}_{\mathrm{PNC}} \epsilon_x] \times (C_{Fm}^{F'm'})^2 \delta_{m,m'\pm 1} \tag{2}$$

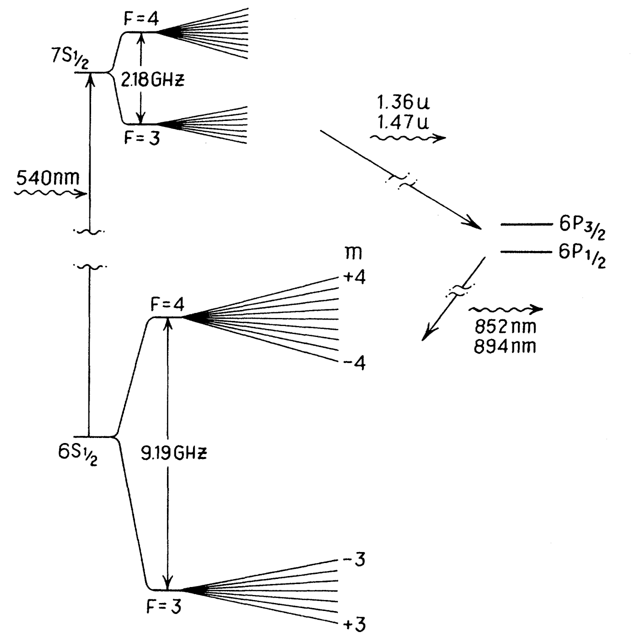

FIG. 1. Cesium energy-level diagram showing hyperfine and weak-field Zeeman structure of $6S$ and $7S$ states.

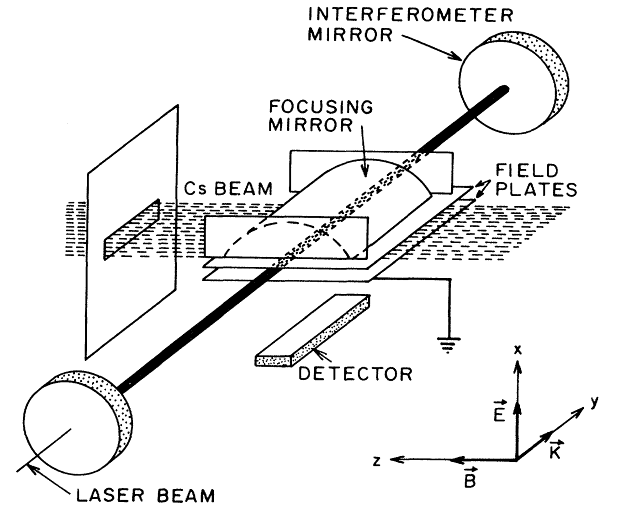

FIG. 2. Interaction region and field configuration.

plus negligibly small terms involving only $\mathscr{E}_{\mathrm{PNC}}$ and A_{M1}. The first term in the brackets is the pure Stark-induced transition rate where β is the vector transition polarizability defined in Ref. 1. The second term is the interference between A_{St} and the much smaller amplitude A_{PNC}. The quantity $i\mathscr{E}_{\mathrm{PNC}}$ is the PNC electric-dipole reduced matrix element. The coefficients C are related to Clebsch-Gordan coefficients and are tabulated in Ref. 6.

In the low-magnetic-field limit, the spectrum of the $F=4\rightarrow 3$ transition is composed of eight lines with strengths, $R(i)$, given by

$$R(i)=I_{4,i-1}^{3,i}+I_{4,i}^{3,i-1}, \tag{3}$$

where $i=-3$ to $+4$. The two outermost lines of the multiplet involve only a single transition ($m=4\rightarrow 3$ and $m=-4$ to -3, respectively) while the other lines are each the sum of a $\Delta m=+1$ and a $\Delta m=-1$ transition. This spectrum (identical to the $F=3\rightarrow 4$ spectrum) is shown in Fig. 3, where the transition rate for each line is the sum of spectra (a) and (b). As we discussed in Ref. 6, the magnetic-field–induced mixing of hyperfine states is small and has no effect on the experiment, although it does cause the slight asymmetry seen in Fig. 3(c).

From Fig. 3 and Eqs. (2) and (3) it is now easy to understand the essence of the experiment. The laser is set to one of the end lines of the multiplet and, by reversing various fields, we change the sign of the PNC interference term without affecting the larger pure Stark-induced rate. Thus we isolate the PNC term by observing the modulation in the transition rate with reversals of the **E** field, the **B** field, and the sign of ϵ_x (handedness of polarization). An additional reversal ("m" reversal) of the interference term is achieved by a change of the laser frequency to the other end of the multiplet. The use of four independent reversals is extremely helpful in the suppression of possible systematic errors.

The experimental setup is similar to that used in

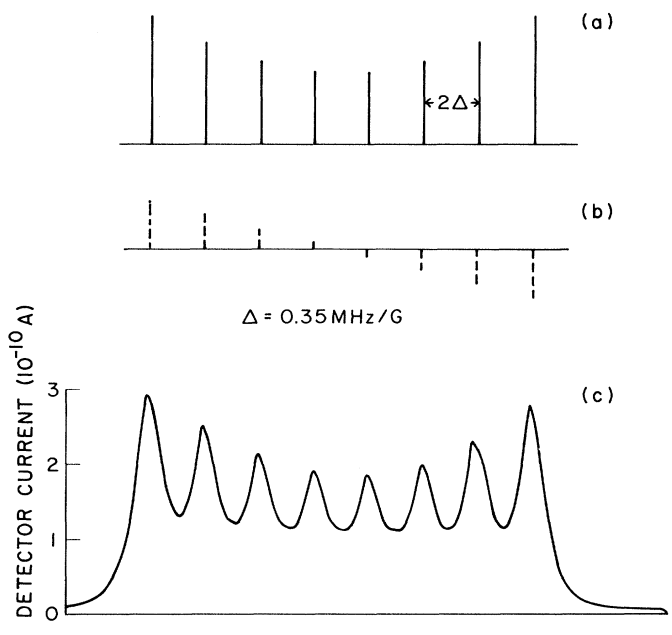

FIG. 3. $6S_{F=4}\rightarrow 7S_{F=3}$ transition. (a) Theoretical pure Stark-induced spectrum. (b) Theoretical parity-nonconserving interference spectrum on expanded scale. (c) Experimental scan of the transition with $B=70$ G.

Ref. 6. About 500 mW of laser light is produced by a ring dye laser at the 540-nm transition frequency. Servocontrol systems provide a high degree of frequency and intensity stabilization. A Pockels cell with $\pm\lambda/4$ voltage applied selects the handedness of the laser polarization. Following the Pockels cell the laser beam enters a Fabry-Perot power-buildup cavity, the length of which is controlled to keep it in resonance with the dye-laser frequency. This produces a standing wave in the cavity with a field which is nearly 20 times larger than the incident field. An intense, well-collimated cesium beam intersects this standing wave at right angles in a line 2.7 cm long. The atomic beam is produced in a two-temperature oven with a capillary-array nozzle followed by a multislit collimator. At the intersection the cesium flux is 1×10^{15} atoms $\text{cm}^{-2}\,\text{s}^{-1}$.

The interaction region is shown in Fig. 2. Situated 2 mm above and below the line of intersection are flat glass plates with transparent electrically conductive coatings. The dc electric field is produced by application of positive or negative voltage to the top plate and grounding of the lower. Data were taken with use of values of the electric field ranging from 2.0 to 3.2 kV/cm. A 70-G magnetic field parallel to the atomic beam is produced by Helmholtz coils.

The $6S\rightarrow7S$ transition rate is monitored by observation of the light which is produced by the $6P_{1/2,3/2}\rightarrow6S$ branch of the $7S$ decay. This light is detected by a cooled silicon photodiode below the lower field plate. A gold cylindrical mirror above the top field plate images the interaction region onto the detector. Colored-glass filters in front of the detector block the scattered green laser light. The detector is carefully shielded to reduce electrical pickup, and is quite insensitive to the magnetic field.

The output of the photodiode is amplified and sent into a gated integrator controlled by a PDP-11/23 computer. This computer also controls the B, E, and P (polarization) reversals. The reversal rates are 0.02, 0.2, and 2 Hz, respectively, with regular 180° phase shifts introduced in the switching cycles. After a brief dead time to avoid transient effects, the detector current is integrated, digitized, and stored for each half cycle of P. The m reversal is done manually every 30 min.

A data run consisted of about 8 h of data accumulation divided equally between the $F=4\rightarrow3$ and $F=3\rightarrow4$ transitions. Systematic error checks (discussed below) were made at the beginning and end of each run. Typical experimental conditions were $E=2500(15)$ V/cm and $\epsilon_x/\epsilon_z=0.94(1)$, giving a detector current of 3×10^{-10} A and a parity-nonconserving fraction of 1.3×10^{-6}. For the data used here the noise was 2 to 3 times worse than the statistical shot-noise limit, primarily because of noise from laser-light-induced fluorescence in the optics. This resulted in an integration time of 20 to 30 min for a $\pm100\%$ measurement of the PNC contribution.

The data were analyzed by finding the fraction of the transition rate, Δ_{PNC}, that modulated with P, E, B, and m. From Eq. (2) it can be seen that $\Delta_{\text{PNC}}=2(\epsilon_x/\epsilon_z)(\text{Im}\,\mathscr{E}_{\text{PNC}}/E\beta)$. A small calibration correction, 5.0(5)%, was made to account for the incomplete resolution of the lines in the multiplet.

Systematic errors, namely, contributions to the signal which mimic the parity nonconservation under all reversals, were a fundamental concern in the design and execution of the experiment. Our approach to the identification and measurement of these contributions was similar to that used in earlier Stark-interference experiments.[3-5] The transition rate was derived for the general case, allowing for all possible components of $\mathbf{E}$, $\mathbf{B}$, $\boldsymbol{\epsilon}$, and the oscillating magnetic field, $\boldsymbol{\epsilon}\times\hat{\mathbf{k}}$. Each of these components was given a reversing and a nonreversing (stray) part. With use of empirically determined limits, all terms which could contribute false signals amounting to greater than 1% of the true PNC were then identified and a set of auxiliary experiments was designed to measure them. These terms and most of the auxiliary experiments have direct counterparts in the work discussed in Refs. 3-5. One test, however, which is unique to this experiment is the *in situ* measurement of the birefringence of the buildup-cavity mirror coatings. Table I shows the results from a typical data run along with all the significant corrections due to false PNC signals. The average of all the data runs has a systematic correction of 14(1)%. As a result of space limitations a detailed discussion of these correction terms will be given in a subsequent paper.

We made a number of other tests to confirm that there are no additional sources of systematic error. Among these were the introduction of known nonreversing fields, misalignments, and birefringences. All of these produced false PNC signals which agreed with the sizes predicted by the calculation discussed

TABLE I. Raw data and corrections to a typical run. ΔE_z and ΔE_y are stray electric fields. ξ represents the birefringence of the buildup-cavity mirror coatings and M is the $M1$ matrix element.

	Fractional modulation ($\times10^6$)
Δ_{PNC} (raw data)	
$4\rightarrow3$	$-1.82(40)$
$3\rightarrow4$	$-1.49(45)$
Corrections	
$\Delta E_z E_y/(E_x^2)$	$-0.02(1)$
$\Delta E_y B_x/(E_x B_z)$	$+0.23(4)$
$M\xi/(\beta E_x)$	$-0.01(2)$

above. Also, analysis of the data showed that on all time scales, from minutes to days, the distribution of values for $\mathrm{Im}\mathscr{E}_{\mathrm{PNC}}/\beta$ was completely statistical. This included data taken with two different sets of buildup-cavity mirrors, different electric-field plates, several complete realignments of the experiment, and different dc electric fields.

Our results are

$$\mathrm{Im}\mathscr{E}_{\mathrm{PNC}}/\beta = \begin{cases} -1.51 \pm 0.18 \text{ mV/cm} & (F=4 \to 3), \\ -1.80 \pm 0.19 \text{ mV/cm} & (F=3 \to 4), \\ -1.65 \pm 0.13 \text{ mV/cm} & (\text{average}), \end{cases}$$

where the uncertainty includes all sources of error. This is in good agreement with the value of $-1.56 \pm 0.17 \pm 0.12$ mV/cm reported by Bouchiat *et al.*[5] for the average of measurements made on the $4 \to 4$ and $3 \to 4$ hyperfine lines. With $\beta = 27.3(4) a_0^3$ (see Ref. 9), we have

$$\mathrm{Im}\mathscr{E}_{\mathrm{PNC}} = -0.88(7) \times 10^{11} e a_0.$$

Using a calculated value for the atomic matrix element we can compare our measurement with the predictions of the standard model for the weak charge, Q_W. Since a discussion of the atomic-physics calculation is beyond the scope of this paper, we will simply take the range of reasonable values to be $\mathscr{E}_{\mathrm{PNC}} = (0.85 \text{ to } 0.97) \times 10^{-11} i e a_0 (Q_W/N)$ and refer the reader elsewhere[10] for a review of this subject. When combined with our measured $\mathscr{E}_{\mathrm{PNC}}$ we obtain $-Q_W$ in the range (71 to 81) ± 6, where 6 is the experimental uncertainty. This is in agreement with the value of 70 ± 4 predicted by the standard model. This agreement provides an improved test of the electroweak theory at low energies and has several specific implications as discussed by Robinett and Rosner[11] and Bouchiat and Piketty.[12] These include improved limits on the radiative corrections to the electroweak theory and on the masses and couplings for additional neutral bosons. From the comparison of the PNC measurements made on the two hyperfine lines[13] we find that the proton-axial-vector–electron-vector coupling constant is $C_{2p} = -2 \pm 2$. This is in agreement with the predicted value of 0.1 and is a substantial improvement over the previous experimental limit of $|C_{2p}| < 100$ (Ref. 5).

To obtain a more precise value for Q_W from future experiments the uncertainty in the atomic theory must be reduced. There are presently a number of groups working on this problem and improvements may well be forthcoming in the near future. It is worth noting that this challenge is leading to new ideas and insights into atomic-structure calculations.

Because the uncertainty is almost entirely statistical we believe that we can achieve significantly higher precision with future refinements to this experiment. The most immediate gain will come from improved optics which will increase the signal size while decreasing the noise. A more substantial change is the use of a spin-polarized atomic beam. This would provide an increase in signal and allow a number of interesting options on the experimental design. We have developed a polarized cesium beam of the necessary purity and intensity[14] and will be exploring these options in the future.

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