Precision Measurement of Parity Nonconservation in Atomic Cesium: A Low-Energy Test of the Electroweak Theory

M. C. Noecker, B. P. Masterson, and C. E. Wieman

Joint Institute for Laboratory Astrophysics, National Bureau of Standards and University of Colorado, and Physics Department, University of Colorado, Boulder, Colorado 80309

(Received 2 May 1988)

We have made an improved measurement of the parity-nonconserving electric-dipole transition amplitude between the 6*S* and 7*S* states of atomic cesium. We obtain $\mathrm{Im}(E_{\mathrm{PNC}})/\beta = -1.576(34)$ mV/cm, which is in good agreement with the predictions of the standard model and earlier less precise measurements. This places more stringent constraints on alternatives to the standard model. We also see the first evidence of a nuclear-spin–dependent contribution to atomic parity nonconservation. The nuclear-spin dependence observed is in agreement with that predicted to arise from a nuclear anapole moment.

PACS numbers: 35.10.Wb, 11.30.Er, 12.15.–y, 21.10.Hw

The measurement of parity nonconservation (PNC) in atoms has the potential to provide tests of the standard model of the electroweak interactions.[1] Such tests complement high-energy tests because they are sensitive to a different combination of the neutral-current electron-quark coupling constants and are at very low energy. Parity nonconservation has been observed in several atoms,[2] but two factors have limited the usefulness of PNC measurements for the testing of the fundamental theory. The first was the limited precision of the experiments, and the second was the limited knowledge of the atomic structure, which is needed to compare the experiments with the electroweak theory. In recent years there has been substantial progress in both areas. Cesium is a particularly attractive atom because of its simple atomic structure. It has a single valence electron outside a tightly bound inner core, which makes the calculations of its structure more tractable. Until now, the accuracy of these calculations has exceeded the precision of the experiments. Previous PNC measurements in cesium have already provided a significant test of the standard model,[1,3,4] and have placed unique constraints on alternatives to the standard model which cannot be obtained from any other data. Here we present a substantially improved measurement of PNC in cesium.

These improved measurements have also provided the first evidence of a nuclear-spin-dependent parity-nonconserving interaction in an atom. It has been predicted that the major source of such an interaction would be the anapole moment of the nucleus, which arises from charged weak interactions between nucleons. The existence of the nuclear anapole moment was predicted many years ago,[5] but it has never been observed.

The experimental technique we use to measure PNC in cesium is the same as we used previously, although we have significantly improved the apparatus. This technique has evolved out of the work of several others in this field and is discussed in detail elsewhere.[6] Here we will only review the basic features. The PNC interaction mixes a small amount of the *P* states into the 6*S* (ground) and 7*S* states of cesium shown in Fig. 1. This gives rise to an electric dipole (*E*1) transition amplitude, E_{PNC}, between these *S* states. We measure this amplitude by observing its interference with a larger electric-field–induced ("Stark") transition amplitude, βE. In the presence of a magnetic field, the interference between these two amplitudes gives a small PNC contribution to the laser-driven $6S \rightarrow 7S$ transition rate. We separate this PNC interference term from the much larger pure Stark-induced rate by determining the fraction of the rate which changes sign with a reversal of the electric

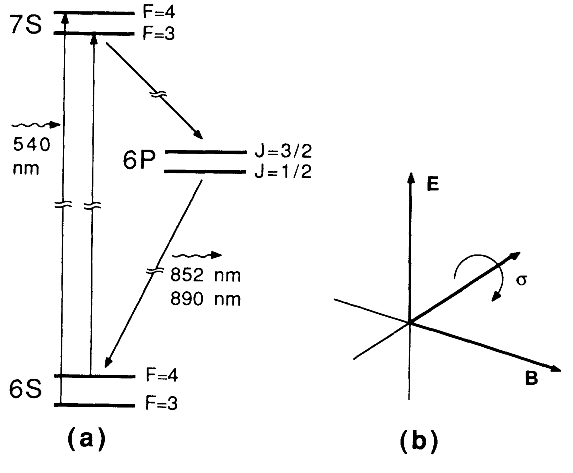

FIG. 1. (a) Cesium energy-level diagram showing relevant transitions. We do not show the small Zeeman splitting caused by the magnetic field. The 540-nm laser light is tuned to one of four different transitions between the 6*S* and 7*S* states. In terms of *F* and *m* quantum numbers, these are (4, ±4 to 3, ±3) and (3, ±3 to 4, ±4). The transitions are detected by observation of the 852- and 890-nm fluorescence. (b) Orientation of the dc electric and magnetic fields and the laser helicity, σ, in the transition region. To observe the PNC modulation we reverse each of these vectors.

field, the magnetic field, the handedness of the laser polarization, and the m quantum number of the level being excited. The parity-conserving rate is unaffected by any of these changes, but the PNC term changes sign with all four. The $6S \rightarrow 7S$ rate is measured by observation of the fluorescence emitted in the decay of the $7S$ state.

The general apparatus is quite similar to that described in Ref. 6; we shall omit a detailed discussion of elements which are described there. An intense, highly collimated beam of atomic cesium intersects a standing wave of circularly polarized light at right angles, in the presence of perpendicular electric and magnetic fields. The standing wave is produced by our sending the light from a tunable dye laser into a Fabry-Perot interferometer power-buildup cavity. The major change from our previous experiment is the use of higher-quality mirrors in this interferometer; their higher reflectivities give a larger signal as a result of the greater power buildup, and their very low birefringence gives much smaller systematic corrections. We have about 800 W circulating power in the cavity—1300 times the power of the laser beam incident on the cavity. Using a rather elaborate servo system, we lock the laser frequency to the cavity resonance, and then the cavity to the chosen cesium resonance frequency. The remainder of the apparatus is identical to that described in Ref. 6, except for a number of small changes that allow more precise alignment of the fields and of the atomic beam. The data-acquisition procedure is similar to that described in Ref. 6. From each day's run we obtain measurements of the fractional PNC rate on the $6S(F=4) \rightarrow 7S(F'=3)$ and $6S(F=3) \rightarrow 7S(F'=4)$ transitions, with a typical fractional uncertainty of 9%. We also make several other measurements to determine misaligned and nonreversing field components that could cause systematic errors.

Investigation of potential systematic errors occupied the great majority of the time spent on the measurement. We have found five different effects that can shift the results by more than 0.1% of the PNC rate, and have corrected the raw data to account for these. The corrections are given in Table I. The first correction accounts for the dilution of the PNC fraction due to overlap from adjacent transition peaks involving other m levels. The other four account for parity-conserving contributions that mimic the PNC rate, changing sign with all four reversals. As shown, these signals arise from misaligned and stray fields, or from interference between the Stark-induced and magnetic dipole ($M1$) amplitudes. The two terms involving stray and misaligned dc fields are very small and are treated in the same manner as before.[6,7] The first $M1$ term, which has also been discussed previously,[6,8] depends on the birefringence upon reflection from the cavity output mirror. Although the reflective coating of this mirror has extraordinarily low intrinsic birefringence, we find it can slowly change because of thin layers of contamination or local deterioration of the coating due to the intense laser fields. To prevent this from introducing significant uncertainty we monitor the birefringence quite closely using the tilted atomic-beam technique discussed in Ref. 6.

The high laser intensities used in this measurement also led to a false signal associated with the $M1$ amplitude on adjacent $\Delta m=0$ transitions; this has not been discussed previously. The high intensities cause a distortion in the resonant line shape of the transition.[9] This shifts the maximum of the atomic resonance signal (to which the laser frequency is locked) to a frequency that is in resonance with atoms that have a nonzero Doppler shift. It can be shown from the discussion by Gilbert *et al.*[10] that this leads to false PNC signal which is proportional to the misalignment of the laser and atomic beams, times the imperfection in the reversal of the laser polarization. We determine the size of this contribution by measuring these two factors, and we minimize it by keeping both quite small. As Table I shows, all the corrections were small and the uncertainties in the corrections, which are also statistical, are much smaller than the statistical uncertainty in a one-day PNC measurement.

We have carried out extensive theoretical analysis and

TABLE I. Systematic corrections to the data as a percentage of the PNC signal.[a]

Systematic contribution	Range	Average all data	Daily uncertainty
(1) Dilution factor	1.4%-5.6%	4.5%	0.3%
(2) $(\Delta E_y/E)(B_x/B)$	−0.3%-+1.1%	0.3%	0.4%
(3) $(\Delta E_z/E)(E_y/E)$	−1.3%-+0.4%	−0.1%	0.4%
(4) $(E1)(M1)$ $(\Delta m=\pm 1)$			
$\Delta F=-1$ line	−0.8%-+4.8%	+1.7%	0.6%
$\Delta F=+1$ line	−1.1%-+6.8%	+2.4%	0.9%
(5) $(E1)(M1)$ $(\Delta m=0)$			
$\Delta F=-1$ line	−0.3%-+0.6%	+0.04%	0.04%
$\Delta F=+1$ line	−1.6%-+0.1%	−0.23%	0.06%

[a] ΔE_y and ΔE_z are nonreversing field components, while B_x and E_y are misaligned components. The range column shows the largest and smallest daily corrections.

many experimental tests in an effort to find and eliminate all possible systematic errors, but when one is measuring such small quantities, there is always the concern that something has been overlooked. To test for this possibility we have carefully analyzed the statistics of the fluctuations in the data. We found that the fluctuations on all time scales showed very good agreement with predictions for purely statistical variations. For example, the set of eighteen daily measurements gave a reduced χ^2 of 1.0 despite several major changes in the apparatus, such as changing the electric-field plates, running at different electric fields, and moving and realigning the interferometer mirrors.

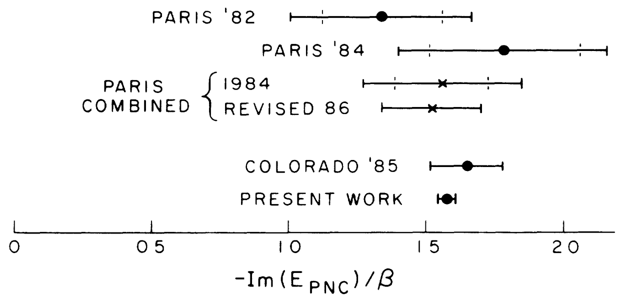

FIG. 2. Comparison of PNC measurements in cesium. From top to bottom, the results shown are from Refs. 11, 12, 12, 13, and 6, respectively.

Our final results for measurements of the ratio of PNC to Stark-induced amplitudes are

$$\mathrm{Im}(E_{\mathrm{PNC}})/\beta=\begin{cases}-1.639(47)(08)\ \mathrm{mV/cm} & (F=4\rightarrow F'=3),\\ -1.513(49)(08)\ \mathrm{mV/cm} & (F=3\rightarrow F'=4),\\ -1.576(34)(08)\ \mathrm{mV/cm} & (\text{average}).\end{cases}\tag{1}$$

The first uncertainty is the statistical uncertainty in the results, and the second is the nonstatistical systematic uncertainty, which is dominated by the uncertainty in the electric-field calibration. We shall combine the two in quadrature in the subsequent discussion. In Fig. 2 we show the various measurements of PNC in atomic cesium. The consistency among the different measurements and the improvement in the precision are clear.

Both the difference and the average of the two measured PNC amplitudes (1) are significant. From the different amplitudes of the two hyperfine lines we find that the nuclear-spin-dependent PNC contribution is +0.126(68) mV/cm. There is a 97% probability that this is larger than zero. Khriplovich and co-workers have discussed the different mechanisms that would lead to a nuclear-spin-dependent parity-nonconserving interaction, which they characterize by the dimensionless coupling constant κ_a.[14,15] From our data and the matrix elements given in Ref. 15 we find $\kappa_a=+0.72(39)$. They have predicted[14] that the nuclear anapole moment would give a value of κ_a in cesium between +0.25 and +0.33. This is the dominant contribution, but there is also a contribution of about +0.05 ($=C_{2P}$) expected from the neutral-current electron-nucleon interaction.[16] The sum of these two gives a predicted $\kappa_a=0.30$ to 0.38, in agreement with our measurement. The uncertainty in the atomic structure is unimportant compared with the large fractional uncertainty in the measurement.

The average PNC amplitude on the two lines, which is almost entirely due to the electron-nucleon neutral-current interaction, was measured with much smaller fractional uncertainty. Thus it can be used to make a quantitative test of the standard model at the few percent level. Our measured PNC amplitude is the product of the weak charge Q_w and an atomic structure factor. To find the value of Q_w, the quantity of interest, one must know the atomic structure factor. There has been considerable recent effort devoted to the improved calculation of this factor for the cesium atom. However, the present uncertainty is still about ±5%,[17] or perhaps slightly less. Although there have been many calculations published, we shall use the average of the results of three recent and rather extensive (and presumably accurate) calculations.[17–19] These span a 5% range. We use the most conservative error estimate (±5%) of the three, and $\beta=27.0a_0^3$.[20] This gives

$$Q_w=-69.4\pm1.5\pm3.8.$$

The first uncertainty is experimental; the second comes from the uncertainty in the atomic structure calculations. Marciano and Sirlin[21] give the renormalized weak charges for the neutron and proton in the standard model in terms of $\sin^2\theta_w$. With these, our value of Q_w gives

$$\sin^2\theta_w=0.219\pm0.007\pm0.018.$$

This result is in agreement with the world average of $\sin^2\theta_w=0.230\pm0.005$ (Ref. 1), which means that the weak charges in Ref. 21 are correct to within the uncertainties.

The confirmation that the standard model is valid in an atomic system at this level of precision implies certain constraints on alternatives to the standard model. These are discussed in detail in Ref. 1. Here we will simply point out one particular aspect of that discussion to emphasize the utility of atomic PNC. This measurement provides the most precise experimental value for the electron axial-vector, down-quark vector coupling constant (C_{1d}). The value of C_{1d} is a sensitive function of the mass of a second neutral boson in many alternative models. A particular class of such models, which has been receiving considerable attention recently, is grand unified theories containing an E_6 group. These results set the best available limits on the masses of such additional neutral bosons.[1,4]

We have carried out a precision measurement of the PNC transition amplitude in atomic cesium. This confirms the standard model of electroweak interactions with an uncertainty of a few percent, and will allow even more precise comparisons of experiment and theory when the calculation of the atomic structure of cesium is improved. These measurements also provide the first evidence of an anapole moment of the nucleus. Work is presently under way to achieve higher experimental precision with use of an optically pumped atomic beam along with other improvements in the experiment. This will allow us to measure the nuclear-spin-dependent PNC effects more precisely, and make precise measurements of parity nonconservation in rubidium.

This work was supported by the National Science Foundation. We are pleased to acknowledge the assistance of Dr. S. Gilbert in the early stages of this work, and valuable conversations with Dr. C. Tanner, Dr. J. Hall, Dr. W. Marciano, Dr. W. Johnson, and Dr. J. Sapirstein.

---

[1] U. Amaldi *et al.*, Phys. Rev. D **36**, 1385 (1987).

[2] E. N. Fortson and L. L. Lewis, Phys. Rep. **113**, 289 (1984).

[3] W. Marciano, in *Proceedings of the Salt Lake City Meeting,* edited by Carleton DeTar and James Ball (World Scientific, Singapore, 1987), p. 319.

[4] S. Capstick and S. Godfrey, Phys. Rev. D **37**, 2466 (1988), and references therein.

[5] Ya. Zel'dovich, Zh. Eksp. Teor. Fiz. **33**, 1531 (1958) [Sov. Phys. JETP **6**, 1184 (1957)].

[6] S. L. Gilbert and C. E. Wieman, Phys. Rev. A **34**, 792 (1986).

[7] P. S. Drell and E. D. Commins, Phys. Rev. A **32**, 2196 (1985).

[8] M. A. Bouchiat, A. Coblentz, J. Guena, and L. Pottier, J. Phys. (Paris) **42**, 985 (1981).

[9] C. E. Wieman, M. C. Noecker, B. P. Masterson, and J. Cooper, Phys. Rev. Lett. **58**, 1738 (1987).

[10] S. L. Gilbert, B. P. Masterson, M. C. Noecker, and C. E. Wieman, Phys. Rev. A **34**, 3509 (1986).

[11] M. A. Bouchiat *et al.*, Phys. Lett. **117B**, 358 (1982).

[12] M. A. Bouchiat *et al.*, Phys. Lett. **134B**, 463 (1984).

[13] M. A. Bouchiat *et al.*, J. Phys. (Paris) **47**, 1709 (1986).

[14] V. Flambaum, I. Kriplovich, and O. Sushkov, Phys. Lett. **146B**, 367 (1984).

[15] P. A. Frantsuzov and I. B. Khriplovich, Z. Phys. D **7**, 297 (1988).

[16] V. N. Novikov *et al.*, Sov. Phys. JETP **46**, 420 (1977).

[17] W. Johnson, S. Blundell, Z. Liu, and J. Sapirstein, Phys. Rev. A **37**, 1395 (1988). The value is 0.95(5) in units of $iea_0(-Q_w/78)\times 10^{-11}$.

[18] V. A. Dzuba *et al.*, Phys. Scr. **36**, 69 (1987). In the same units as above, this value is 0.90(2).

[19] C. Bouchiat and C. A. Piketty, Europhys. Lett. **2**, 511 (1986). In the same units as above, this value is 0.935(2)(3). Reference 17 and 18 are *ab initio* calculations; this is a semiempirical result.

[20] We are breaking with the tradition of using a semiempirical value for β, and instead are using a theoretical value. There are two ways to obtain a reliable theoretical value: using theoretical oscillator strengths from V. Dzuba *et al.*, J. Phys. B **18**, 597 (1985), or taking the calculated value for β given in a paper by Z. W. Liu and W. Johnson, presented at the Annual Meeting of the Division of Atomic, Molecular, and Optical Physics of the American Physical Society, Cambridge, Massachusetts, 18–20 May 1987 (unpublished). The two values obtained in this way agree with each other and the semiempirical result to within 1%, which is less than the semiempirical uncertainty. We have used the average of the two theoretical results. Q_w now is obtained from the quotient of two atomic properties calculated in a similar way. Since both of these quantities tend to behave the same way as higher-order corrections are added, this treatment should minimize the error due to the atomic structure calculation.

[21] W. J. Marciano and A. Sirlin, Phys. Rev. D **27**, 552 (1983).