Precise Measurement of Parity Nonconserving Optical Rotation at 876 nm in Atomic Bismuth

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We report the first precise measurements of parity nonconserving (PNC) optical rotation in atoms, carried out on the 876-nm $M1$ transition in bismuth. We obtain $R_i = \mathrm{Im}(E1_{\rm PNC}/M1) = (-10.12 \pm 0.20)\times 10^{-8}$, where $E1_{\rm PNC}$ is the $E1$ amplitude mixed into the transition by the nuclear spin-independent PNC interaction. The result is in excellent agreement with the standard model of the electroweak interaction. The amplitude of nuclear spin-dependent PNC rotation is found to be less than 1.5×10^{-2} of that due to the nuclear spin-independent interaction.

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Parity nonconserving (PNC) effects in atoms are predicted by the standard model of the electroweak interaction [1,2]; measurements have been carried out in cesium [3,4] and thallium [5] by the technique of Stark interference, and in lead [6], thallium [7], and bismuth [8–12] by optical rotation. The work complements high-energy studies of electroweak processes; in principle, one can test calculations of radiative corrections and investigate physics beyond the standard model [13]. Atomic PNC measurements are also sensitive to the nuclear anapole interaction, which appears as a nuclear spin-dependent term in the PNC Hamiltonian, expected to be larger than that due to Z^0 exchange between the nucleus and electrons [14]. However, for such applications, one needs an experimental precision of order 1% or better. Despite well over a decade of effort, only a single experiment, on cesium [4], has approached this level. The present work brings the total to two.

We measure as a function of frequency ν the optical rotation $\phi(\nu)$ produced by a known optical depth of bismuth vapor in the vicinity of the 876-nm allowed $M1$ transition ($6p^3\ J'=\frac{3}{2} \rightarrow 6p^3\ J=\frac{3}{2}$, where J',J refer to the lower and upper levels, respectively). Our earlier publication [11], which reported a preliminary measurement to 10% accuracy, gives a description of the experiment. The nuclear spin-independent and spin-dependent PNC rotations have theoretical forms ϕ_i and ϕ_s, respectively (Fig. 1):

$$\phi_i(\nu) = PR_i \sum_{F,F'} K_i(F,F')D(\nu_{F,F'}-\nu)\,,$$

$$\phi_s(\nu) = PR_s \sum_{F,F'} K_s(F,F')D(\nu_{F,F'}-\nu)\,.$$

The electroweak theory enters through R_i and R_s, values of which were determined in the experiment. They are defined by $R_i = \mathrm{Im}\langle E1^i\rangle/\langle M1\rangle$, $R_s = \mathrm{Im}\langle E1^s\rangle/\langle M1\rangle$, where $\langle E1^i\rangle$, $\langle E1^s\rangle$, and $\langle M1\rangle$ are reduced matrix elements evaluated between the stretched states $F=I+J$, $F'=I+J'$. $\langle E1^i\rangle$ and $\langle E1^s\rangle$ represent respectively the electric dipole amplitudes mixed into the $M1$ transition by the nuclear spin-independent and spin-dependent components of the interaction. This definition of R_i is equivalent to the conventional one as given in the abstract. The optical depth factor P is given by

$$P = \frac{\pi\mu_0}{3\lambda\hbar}\frac{|\langle M1\rangle|^2}{(2I+1)(2J'+1)}\int N(x)dx\,,$$

where $\int N(x)dx$ is the line integral of the number density along the light path. The function $D(\nu_{F,F'}-\nu)$ is a nor-

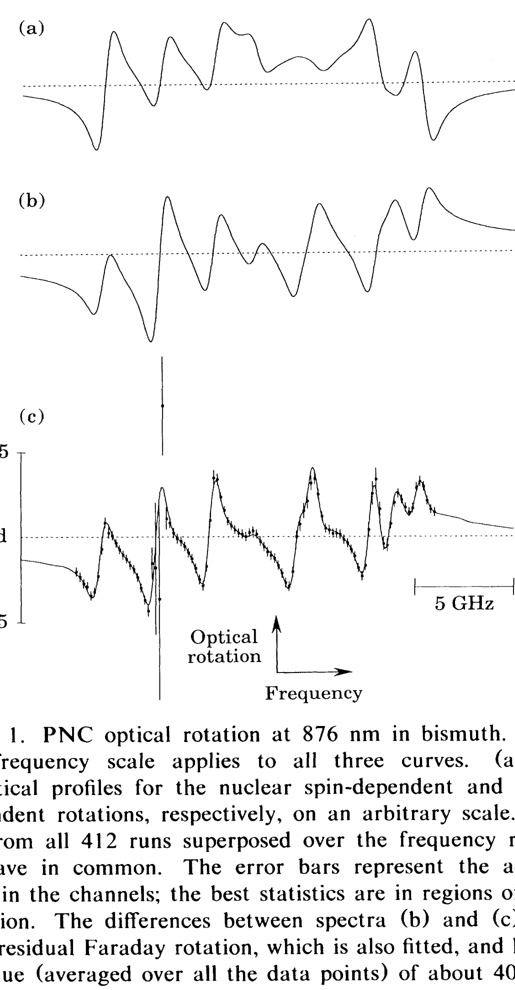

FIG. 1. PNC optical rotation at 876 nm in bismuth. The same frequency scale applies to all three curves. (a),(b) Theoretical profiles for the nuclear spin-dependent and spin-independent rotations, respectively, on an arbitrary scale. (c) Data from all 412 runs superposed over the frequency range they have in common. The error bars represent the actual scatter in the channels; the best statistics are in regions of low absorption. The differences between spectra (b) and (c) are due to residual Faraday rotation, which is also fitted, and has a rms value (averaged over all the data points) of about 40% of the PNC rotation.

malized Doppler-broadened dispersion line shape [15] centered on the hyperfine component $F \rightarrow F'$. The coefficients $K_i(F,F')$ and $K_s(F,F')$ can be shown by standard methods to be given by

$$K_i(F,F') = (2F+1)(2F'+1)\begin{Bmatrix} F & F' & I \\ J' & J & 1 \end{Bmatrix}^2 ,$$

$$K_s(F,F') = (-1)^{I+J+F'+1}(2F+1)(2F'+1)\begin{Bmatrix} F & F' & I \\ J' & J & 1 \end{Bmatrix} \times \sum_{k=0}^{2} \eta_k (2k+1)^{1/2} \begin{Bmatrix} I & I & 1 \\ J' & J & k \\ F' & F & 1 \end{Bmatrix} .$$

The $K_s(F,F')$ depend slightly on the electronic coupling scheme through the numerical factors η_k. For our final results we used the values $\eta_0 = 0.19$, $\eta_1 = -8.0$, $\eta_2 = -7.1$ (deduced from Ref. [16]) which take into account the breakdown of jj coupling, but data were also analyzed with the values 0, $-\sqrt{55}$, $-\sqrt{55}$ appropriate to jj coupling and the differences were insignificant. When computed over the entire range of the hyperfine structure, ϕ_i and ϕ_s are closely orthogonal both to each other and to the other significant contribution to the spectrum, Faraday rotation. As a result, the three can be separated in the data analysis. Bismuth-independent rotations are subtracted out by recording rotation spectra with and without bismuth in the light path.

The improvement in precision over our previous work [11] is due to the greatly increased reliability of the system, the reduction of noise sources, and changes in experimental procedure. These have enabled us to take far more data of higher quality under better controlled conditions. The statistical uncertainty has been reduced by a factor of about 5. Comparable amounts of data with each of six permutations of polarizer and analyzer orientations have been obtained, making the tests for systematic effects much more critical than before. Major improvements have been the installation of a new laser system, which scans reliably and reproducibly, and a new oven, which operates under constant and controlled conditions for long periods. Other refinements include the reduction of noise due to laser frequency fluctuations [11]. A detailed mathematical model of the system which includes all known noise sources is used to optimize the choice of experimental parameters and procedure, also to test the performance of the system against theoretical predictions for any given set of conditions.

An experimental run consisted of eight scans (denoted Bi) on bismuth and eight scans (e) on the empty tube, giving mean rotation and absorption spectra as previously described [11]. Each scan involved measurements at 200 frequency points, and took about 50 sec. A fit to the absorption spectrum gave values of P and of the Lorentzian and Gaussian widths, typically 350 and 650 MHz, respectively (the hyperfine splitting factors of the levels are accurately known [15]). The mean rotation spectrum (bismuth minus empty tube) was then fitted by a composite curve of the form

$$\bar{\phi}(\text{Bi-}e) = \phi_i(\nu) + \phi_s(\nu) + \phi_F(\nu) + Q(\nu) ,$$

for which the frequency scale, line-shape parameters, and optical depth were already known. The functions $\phi_i(\nu)$ and $\phi_s(\nu)$ were therefore completely specified apart from the values of R_i and R_s, respectively, so the fit gave a determination of these quantities. The function $\phi_F(\nu)$ representing the Faraday-rotation spectrum was also completely specified apart from a scaling factor proportional to the strength of the residual magnetic field. The Faraday effect in the 876-nm transition has been studied theoretically and experimentally [15], and is well understood; it is present at the level of the PNC rotation or less in our runs. Any unsubtracted background was represented as a quadratic in frequency $Q(\nu)$, so that a total of six parameters were adjusted in fitting the rotation spectra. All fitting was carried out using weighting functions based on the frequency dependence of the signal-to-noise ratio expected according to our model. The noise contributions were measured in separate experiments.

In all, 412 runs were taken under a variety of conditions; the results are shown in Table I (see also Fig. 1). We consider first R_i. From the statistics of the fitting to an individual run, the value of R_i is subject to an uncertainty of about 10% giving a predicted uncertainty in the mean of all the runs of 0.5%, to be compared with the actual value of 0.7%. Any effects produced by the variations in conditions are thus at the margin of what can be detected by statistical tests. Runs were taken in sequences of 4 during which the operating conditions of the system were unaltered. Random changes were carried out to the positions of optical components in between each sequence so as to change completely the character of the bismuth-independent rotation spectrum. There was no significant correlation between the results within a sequence. Results were obtained with the polarization of the input light in three different directions because some features of the apparatus define axes perpendicular to the propagation direction. No effect was found.

The axis of the analyzer was rotated through 180° after about half the runs taken with each polarizer orientation to test for effects associated with inhomogeneity in the bismuth vapor [12]. None were apparent. Statistical tests were carried out to discover whether the values of R_i obtained in the runs were correlated with the amount of Faraday rotation present, the optical depth, and the parameters used to describe the background rotation in the function $Q(\nu)$. The data were also reanalyzed with different weighting functions and different methods of parametrizing the background rotation. In no case was there significant evidence for the existence of systematic effects. However, the sensitivity of our tests is of the order of the statistical uncertainty, so we cannot exclude systematic effects at a level of better than 1%. Including an allowance for the 0.5% uncertainty in the calibration

TABLE I. Results for R_i and R_s at various orientations of the transmission axis of the polarizer P to the vertical. In each case about half the data were taken in each of the two possible crossed positions of the analyzer A. The errors given are purely statistical (1 standard deviation).

P	A	10^8R_i		10^8R_s	
+90°	180°	−10.13(21)	−10.13(14)	0.03(14)	0.04(10)
	0°	−10.13(21)		0.04(14)	
+45°	+135°	−10.21(20)	−10.26(13)	−0.20(18)	0.07(11)
	−45°	−10.31(18)		0.30(11)	
0°	+90°	−9.98(17)	−10.03(11)	−0.16(10)	−0.12(7)
	−90°	−10.07(15)		−0.08(11)	
Grand mean			−10.12(07)		−0.02(5)

of the polarimeter, we quote finally

$$10^8R_i = -10.12 \pm 0.20.$$

This result is in good agreement with the previously published values of -10.4 ± 1.7 [10] and -10.0 ± 1.0 [11]. To interpret it we write $R_i = \zeta G_F Q_W$, where G_F is the Fermi constant, Q_W the weak nuclear charge [17], and ζ an atomic structure factor. The traditional approach is to extract a value of Q_W, and hence of $\sin^2\theta_W$, where θ_W is the Weinberg angle. However, it is more straightforward to work in terms of M_Z, the Z^0 mass. Atomic PNC in heavy elements depends on the parameters of the standard model almost entirely through M_Z [17,18], and is highly insensitive to the unknown Higgs or top-quark masses M_H and M_t even when radiative corrections are included. This can be understood from the recent demonstration [13] that within the standard model the product $G_F Q_W$ is to an excellent approximation independent of $\sin^2\theta_W$ for heavy elements, and is in fact proportional to M_Z^{-2}. We can therefore extract a value of M_Z from the experiment, free from uncertainties attributable to M_H and M_t, which can be directly compared with the result 91.177 ± 0.022 GeV from CERN (Conseil Europeen pour la Recherche Nucleaire) [19]. Using the expressions of Ref. [13], and the most precise atomic calculations [20] for this transition, which give $\zeta G_F = (11.0 \pm 1.3) \times 10^{-8} N$, where the neutron number $N = 126$, we obtain $M_Z = 92 \pm 5$ GeV. The excellent agreement despite the difference of some 10 orders of magnitude in the square of the four-momentum transfer at which the experiments were carried out confirms the success of the standard model over this enormous range. The uncertainty, though less than in any other element except cesium, is now dominated by atomic calculations, and the present experimental result, which is accurate enough to be sensitive to radiative corrections, offers a clear incentive to improve them.

The statistical and correlation tests described above for R_i were also applied in the case of R_s. The only evidence for systematic effects was a scatter larger than that predicted by statistics among the different analyzer orientations. The orientation itself is unlikely to be the underlying cause, since any deflection of the laser beam will have the frequency dependence of ϕ_i rather than ϕ_s, and the scatter does not appear in the values of R_i. The uncertainty in the final result,

$$10^8R_s = -0.02 \pm 0.15,$$

includes an allowance for this nonstatistical behavior.

Despite the high sensitivity of the experiment to nuclear spin-dependent rotation, the uncertainty is still much too large to allow us to observe an effect because the transition itself is particularly unfavorable. There are expected to be two contributions to R_s, one due to Z^0 exchange between electrons and the nucleus and the other the nuclear anapole interaction, characterized by coupling constants C_{2n} (n for nucleus, not nucleon) and κ_a, respectively [14,21,22]. It can be shown by standard methods that for this transition, within jj coupling (which is adequate for the present purposes),

$$R_s = -\frac{\zeta G_F}{N}\frac{2I}{3(I+1)}C'_{2n},$$

where the effective coupling constant [21]

$$C'_{2n} = C_{2n} - \kappa_a(I+\tfrac{1}{2})/I.$$

We thus obtain

$$C'_{2n}(\mathrm{Bi}) = 0.4 \pm 3.2.$$

Neither C_{2n} nor κ_a can be calculated with any confidence because of nuclear structure and strong interaction effects, but the anapole is generally assumed to be the larger contribution, and estimates for κ_a(Bi) vary from 0.08 to 0.45 [21,22]. It would therefore be very difficult to make a significant measurement of nuclear spin-dependent effects in this transition. The $M1$ transition at 648 nm in bismuth offers a better prospect, being about 3 times more sensitive to the interaction.

Because of the simple dependence on M_Z, high-precision atomic PNC experiments offer a critical test of the standard model at low energies, particularly of radiative corrections to the theory. The optical rotation and fluorescence techniques are now both at the level where they are sensitive to radiative corrections, and both can be improved further. The present experiment, and others which can now be expected to follow, presents a challenge to atomic theory to allow the measurements to be interpreted at the same level as the experimental precision.

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[1] M. A. Bouchiat and C. C. Bouchiat, Phys. Lett. **48B**, 111 (1974).
[2] E. A. Hinds, in *Atomic Physics 12,* edited by S. Haroche, J. C. Gay, and G. Grynberg (World Scientific, Singapore, 1989).
[3] M. A. Bouchiat *et al.*, J. Phys. (Paris) **47**, 1709 (1986).
[4] M. C. Noecker, B. P. Masterson, and C. E. Wieman, Phys. Rev. Lett. **61**, 310 (1988).
[5] P. S. Drell and E. D. Commins, Phys. Rev. Lett. **53**, 968 (1984).
[6] T. P. Emmons, J. M. Reeves, and E. N. Fortson, Phys. Rev. Lett. **51**, 2089 (1983).
[7] T. M. Wolfenden, P. E. G. Baird, and P. G. H. Sandars, J. Phys. B (to be published).
[8] L. M. Barkov and M. S. Zolotorev, Zh. Eksp. Teor. Fiz. **79**, 713 (1980) [Sov. Phys. JETP **52**, 360 (1989)].
[9] G. N. Birich *et al.*, Zh. Eksp. Teor. Fiz. **87**, 776 (1984) [Sov. Phys. JETP **60**, 442 (1984)].
[10] J. H. Hollister *et al.*, Phys. Rev. Lett. **46**, 643 (1981).
[11] M. J. Macpherson *et al.*, Europhys. Lett. **4**, 811 (1987).
[12] J. D. Taylor *et al.*, J. Phys. B **20**, 5423 (1987).
[13] P. G. H. Sandars, J. Phys. B **23**, L655 (1990).
[14] V. V. Flambaum and I. B. Khriplovich, Zh. Eksp. Teor. Fiz. **79**, 1656 (1980) [Sov. Phys. JETP **52**, 835 (1980)].
[15] K. M. J. Tregido *et al.*, J. Phys. B **19**, 1143 (1986).
[16] V. V. Novikov *et al.*, Zh. Eksp. Teor. Fiz. **73**, 802 (1977) [Sov. Phys. JETP **46**, 420 (1977)].
[17] S. A. Blundell, W. R. Johnson, and J. Sapirstein, Phys. Rev. Lett. **65**, 1411 (1990).
[18] B. W. Lynn, in *Proceedings of the 1983 Trieste Workshop on Radiative Corrections in $SU(2)_L \times U(1)$, Trieste, Italy, 1983,* edited by B. W. Lynn and J. Wheater (World Scientific, Singapore, 1984).
[19] DELPHI Collaboration, CERN Report No. PPE/91-95, 1991 (to be published).
[20] V. A. Dzuba, V. V. Flambaum, and O. P. Sushkov, Phys. Lett. A **141**, 147 (1989).
[21] C. Bouchiat and C. A. Piketty, Z. Phys. C **49**, 91 (1991).
[22] V. V. Flambaum, I. B. Khriplovich, and O. Sushkov, Phys. Lett. **146B**, 367 (1984).