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Upper Limit on Parity-Nonconserving Optical Rotation in Atomic Bismuth

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We have searched for optical rotation near the 8757-Å magnetic-dipole absorption line in atomic bismuth vapor. The experiment is sensitive to parity nonconservation in the weak neutral-current interaction between electrons and nucleons in atoms. We find $R \equiv \mathrm{Im}(E_1/M_1) = (-0.7 \pm 3.2) \times 10^{-8}$, which is considerably smaller than the value $R = -2.5 \times 10^{-7}$ obtained by central-field calculations for this bismuth line using the Weinberg-Salam theory of neutral currents.

We present here results of an experiment in which we search for parity-nonconserving (PNC) optical rotation in atomic bismuth vapor.[1,2] We set an upper limit to PNC rotation that is significantly below the value calculated[3-6] for bismuth on the basis of the Weinberg-Salam theory[7,8] of neutral currents.

We look near a magnetic-dipole absorption line where optical rotation would result from interference between the normal magnetic-dipole amplitude M_1 and an electric-dipole amplitude E_1 added to the transition by PNC forces in the atoms. The rotation angle[9] has the form $\varphi_{\mathrm{PNC}} = -4\pi\lambda^{-1}(n-1)lR$, where $R \equiv \mathrm{Im}(E_1/M_1)$, l is the length of vapor, λ the wavelength, and n the refractive index due to the M_1 transition. The refractive index depends upon λ and has a dispersion shape near the transition which is useful for separating φ_{PNC} from background rotations. For an atomic density giving one absorption length at line center, $\varphi_{\mathrm{PNC}} = R/2$ at a dispersion peak. Increasing the atomic density can produce a rotation much larger than R just outside the absorption line, where in favorable cases such as ours the usable optical depth $(n-1)l$ is not strongly limited by absorption.

Heavy atoms are a good place to look for neutral-current effects, which increase rapidly[10] with the atomic number Z. Bismuth ($Z=83$) has several allowed magnetic-dipole transitions from its ground state accessible to tunable lasers. We selected the $J=\frac{3}{2} \rightarrow J=\frac{3}{2}$ absorption line at 8757 Å where there is no competing background absorption from Bi_2 molecular bands to limit the usable optical depth outside the atomic line.

In Table I we list values of R for the 8757-Å line calculated by various forms of relativistic central-field approximation. The ±30% agreement is encouraging considering the differing methods, but more complete calculations that include many-particle effects are clearly desirable.

The basic apparatus and the procedure we use for measuring small angles of optical rotation were both described in Ref. 2. We have since made important additions to the apparatus, which include higher-quality Nicol prism polarizers (obtained from the Karl Lambrecht Co. and transmitting less than 10^{-8} when crossed), a more uniformly heated Bi oven, and Permalloy magnetic

TABLE I. Relativistic central-field calculations of $R \equiv \mathrm{Im}(E_1/M_1)$ for the 8757-Å line in Bi, using the Weinberg-Salam theory (Refs. 8 and 9) with a Weinberg angle given by $\sin^2\theta_W = 0.35$.

Ref. no.	Method	$R(10^{-7})$
3	Hartree-Fock	-2.3
4	Hartree-Fock	-3.5
5	Semiempirical	-1.7
6	Multiconfiguration	-2.4

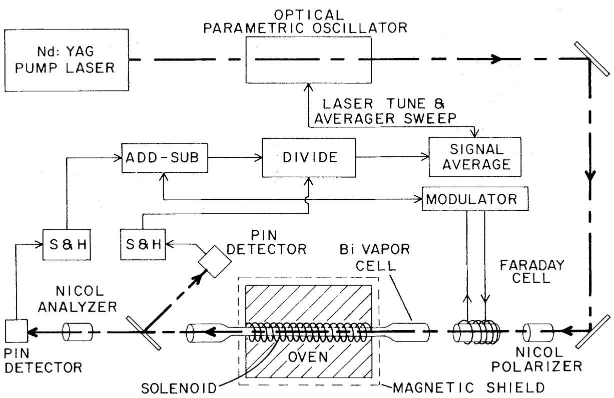

FIG. 1. Schematic view of the apparatus.

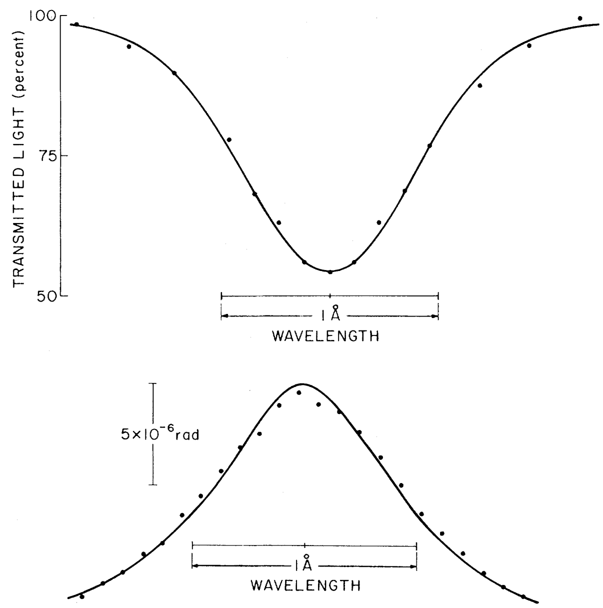

FIG. 2. The 8757-Å magnetic-dipole transition scanned by the laser, with data points and expected curves for (a) absorption and (b) Faraday rotation in 0.1 G.

shielding used on some runs to insure a negligible Bi Faraday rotation. The laser sweep is controlled so as to lock the position of the absorption line within the sweep. Also, the electronics has been upgraded by the addition of a PDP-8 computer to process the signals and store the data.

A schematic view of the entire experiment is shown in Fig. 1. The light source is a tunable Chromatix Model 1020 pulsed parametric laser. The laser beam traverses a path consisting of two nearly crossed Nicol polarizers, with the bismuth vapor cell and polarization modulator (a water-filled Faraday cell) between them. A silicon diode (p-i-n) detector converts transmitted light to an electrical signal that is amplified and sent to a sample-and-hold circuit triggered by each laser pulse. The signals are added and subtracted synchronously with the Faraday cell modulation and are then divided in the computer by a reference signal derived from light reflected just before the second Nicol prism. The resultant signal, which is then sensitive mainly to optical rotation in the Bi cell, is stored in the computer as a function of the laser frequency setting.

We have used a Fabry-Perot interferometer to analyze both the laser light and the 8757-Å absorption line. The laser has approximately a Gaussian line shape with a width that can be varied between 0.5 and 1.0 Å. The absorption line, with ten hfs components spread over a total interval of 0.4 Å, is not resolved by the laser. Under the Fabry-Perot analysis the absorption shows a profile[11] which agrees with the relative intensities expected for the hfs components of this line. With this well-characterized profile shape, a single parameter which we will call the absorption strength[12] then suffices to specify completely the absorption, and also φ_{PNC} for a given value of R.

To determine the absorption strength conveniently during the operation of the experiment, we use the Faraday rotation described below.

Figure 2(a) shows absorption of the laser light recorded using the reference signal during a sweep of the center frequency of the laser across the absorption line. The measured points agree with the absorption curve calculated from the mutual overlap of the wavelength profiles of the laser and absorption line, using the absorption strength of the line as a free parameter to adjust the fit. Laser absorption becomes insensitive to the absorption strength once tha atomic density gives several absorption lengths within the line profile.

An axial magnetic field along the Bi tube produces in the laser light a Faraday rotation φ_{F} associated with the absorption line. The rotation may be readily calculated from the known g values and spacings of the hfs levels.

Figure 2(b) shows measurements of φ_{F} taken by sweeping the laser across the 8757-Å line with the axial magnetic field set at 0.1 G. The experimental points fall very close to the theoretical curve obtained by averaging the computed Faraday rotation and transmitted light intensity over the laser line shape,[13] with the absorption strength the only free parameter in the fit. The value of φ_{F} thus provides an independent measure of the absorption strength at a given Bi vapor temperature and it agrees to within 15% with the Fabry-Perot measurements of absorption.

To search for φ_{PNC} we look for a rotation feature with a dispersion shape that is mainly antisymmetrical about the absorption line center. We set φ_F close to zero by adjusting the axial field to eliminate rotation signals symmetric about line center. The far smaller antisymmetric part of φ_F is then almost negligible. There remains a residual rotation, caused mainly by small imperfections in the polarizers, which typically varies with λ by about 4×10^{-7} rad/Å. This residual λ dependence tends to average out with changes in the optical alignment to which it is quite sensitive. Any remainder can be rejected further by fitting the data to the form of the φ_{PNC} dispersion curve.

Our experimental procedure for taking the data reported here consisted of making repeated laser scans across the absorption line with φ_F nulled, while recording the accumulated rotation signal as a function of laser wavelength. After ten such scans, a separately recorded scan was taken with an applied axial field of 0.1 G to determine the absorption strength by measuring φ_F. After changing the optical alignment to insure a different instrumental residual rotation, the procedure was repeated.

In our analysis, we utilize data only well outside the region of strong absorption of the laser light. We thereby avoid possible systematic uncertainties[14] we reported with our earlier results in Ref. 1. In the wings of the line, the interpretation is straightforward since φ_{PNC} is there sensitive mainly to the magnitude rather than the details of the absorption. In addition any small remaining antisymmetric part of φ_F becomes totally negligible in the wings of the line.

Figure 3 shows one set of our data taken in 300 scans of the absorption line at a bismuth temperature near 1500 K. The rotations have been subtracted symmetrically about line center to display only antisymmetric effects. The solid curve in Fig. 3 gives the expected variation in φ_{PNC} for $R = -2.5\times10^{-7}$ which is taken as approximately the mean value in Table I. The dashed line is simply a Gaussian dispersion curve calculated with the same value of R and same integrated absorption. It is clear that the two curves are almost identical in the region of interest and therefore details of the absorption line should have little effect on our results. The data clearly show no feature of the form and magnitude expected with the assumed value of R.

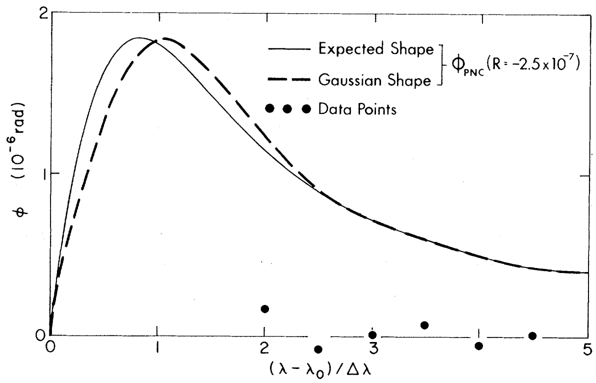

FIG. 3. The optical-rotation data points and predicted curves (see text) for $R = -2.5\times10^{-7}$, subtracted symmetrically about the line center at λ_0, and plotted in units of the absorption half-width $\Delta\lambda$.

Our overall result, deduced from a total of 1500 scans of the absorption line, which represents about 20 hours of actual running time, is $R = (-0.7\pm3.2)\times10^{-8}$. The quoted uncertainty is 1.5 standard deviations (roughly a 90% confidence limit), and is derived from the observed random variations of our data from one scan to the next. This result is in substantial disagreement with all the calculated values of R shown in Table I. The following Letter,[15] which describes an independent experiment at Oxford using the 6476-Å absorption line in bismuch, reports a similar result.

We are presently installing a laser with better wavelength resolution, which should improve further the accuracy in bismuth. We have begun also a similar optical rotation experiment on the M_1 line in thallium at 1.28 μm.

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[11]Collisional broadening becomes noticeable for He buffer gas pressures above 100 Torr, but no observable collisional enhancement of the integrated absorption of this M_1 line occurs.

[12]A convenient parameter is the mean number of absorption lengths of the hfs components at their peaks.

[13]The central dip associated with the Faraday effect disappears in the average over the transmitted laser light for conditions of strong absorption as in Fig. 2(b).

[14]The average over the laser profile of any λ-dependent background rotation will change when the absorption line alters the transmitted laser profile.

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Search for Parity-Nonconserving Optical Rotation in Atomic Bismuth

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We report the results of a laser experiment to search for the parity-nonconserving optical rotation in atomic bismuth. We work at wavelengths close to the 648-nm $J=3/2$—$J=5/2$ M_1 transition from the ground state. We find $R=\mathrm{Im}(E_1/M_1)=(+2.7\pm4.7)\times10^{-8}$, in disagreement with the theoretical value $R=-30\times10^{-8}$ predicted for this transition on the basis of the Weinberg-Salam model of the weak interactions combined with relativistic central-field atomic theory.

We report the results of an experiment to search for the parity-nonconserving (PNC) optical rotation[1-4] in atomic bismuth which has been predicted[5-7] on the basis of the Weinberg-Salam[8] model of the weak interactions. We have made measurements close to the allowed M_1 transition at 648 nm ($6p^3J=\frac{3}{2}\rightarrow6p^3J=\frac{5}{2}$).[10] In this initial experiment we have worked only in the vicinity of the most intense hyperfine component ($F=6-7$) since it is well separated from the rest of the pattern.

Close to the transition, the PNC optical rotation is predicted to have a dispersive shape; $\varphi_{\mathrm{PNC}}=-4\pi[(n-1)LR/\lambda]$ where n is the refractive index, L the path length, λ the wavelength, and $R=\mathrm{Im}(E_1/M_1)$ is the ratio of the PNC transition matrix element E_1 to the normal magnetic-dipole element M_1. We have worked with a bismuth vapor pressure corresponding approximately to one atomic absorption length at peak, which gives a rotation φ_{PNC} close to $R/2$ at the maximum of the dispersion curve.

A number of relativistic central-field calculations of R have been made for the transition 648 nm.[5,6] The effect of the various approximations in a calculation of this type is difficult to assess, and the ±30% agreement is reasonable considering the different approaches employed.

Our apparatus is illustrated schematically in Fig. 1. The Spectra-Physics 580A jet-stream dye laser produces approximately 2 mW of light in a bandwidth of a few megacycles. The essentials of the optical system consist of a pair of crossed polarizers with the bismuth oven between them. The oven assembly is shown separately in Fig. 2.

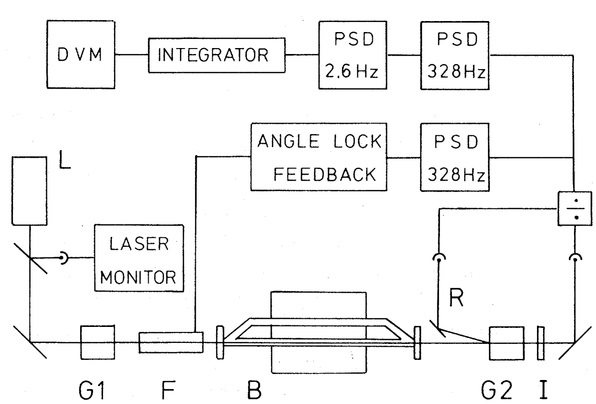

FIG. 1. Schematic diagram of appartus. L, dye laser; $G1$, $G2$ crossed Glan-Thompson polarisers; F, Faraday modulator; B, bismuth oven; I, interference filter; R, intensity reference. The slow "angle lock feedback" controls a dc field applied to F (see text).