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Measurement of Parity Nonconservation in Atomic Bismuth

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Parity-nonconserving optical rotation has been observed and measured on the 8757-Å magnetic-dipole absorption line in atomic bismuth vapor. The result, $R \equiv \text{Im}(E_1/M_1) = (-10.4 \pm 1.7) \times 10^{-8}$, is of the approximate size calculated with use of the Weinberg-Salam theory of the weak neutral-current interaction with $\sin^2\theta_W = 0.23$.

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We report here the result of a series of measurements of optical rotation in atomic bismuth vapor at the 8757-Å magnetic-dipole absorption line. The appearance of parity-nonconserving (PNC) optical rotation induced by the weak neutral-current interaction between the atomic electrons and nucleons is a significant prediction of the Weinberg-Salam theory^{1,2} of weak interactions. The effect is largest in heavy atoms.^{3,4} Our measurements reveal a well-resolved optical rotation that agrees in sign and approximate magnitude with recent calculations of the effect in bismuth based on the Weinberg-Salam theory.

Since the time of our earliest measurements^{5,6} on this bismuth line, which were not mutually consistent, we have added a new laser, improved the optics, and included far more extensive systematic checks. Our present result (see Table I below) is based on many separate measurements made over the past two years (data collection periods I-V), all in good agreement with each other.

Although a PNC neutral-current interaction between electrons and nucleons in agreement with the Weinberg-Salam theory has been observed in high-energy electron scattering,⁷ the situation in atoms is unclear. Our experiment and the bismuth optical-rotation experiments by three other groups⁸⁻¹⁰ have yielded results with significant mutual discrepancies far larger than quoted errors. The overall evidence possibly favors some PNC effect in bismuth,⁴ and similar evidence about thallium comes from measurements at

Berkeley of circular dichroism in thallium vapor.¹¹

We determine the quantity $R \equiv \text{Im}(E_1/M_1)$, where M_1 is the magnetic-dipole amplitude of the absorption line and E_1 is the electric-dipole amplitude coupled into the same line by the PNC interaction between the atomic electrons and nucleons. The two dipoles combine to produce a rotation of the plane of polarized light in bismuth vapor by an angle $\varphi_{\text{PNC}} = -4\pi l \lambda^{-1} (n-1)R$, where n is the refractive index due to the magnetic-dipole line, λ is the wavelength, and l the path length. Sharp dispersive changes in φ_{PNC} at each hyperfine component of the line help to distinguish the signal from background rotations.

The plan of the experiment is shown in Fig. 1. A tunable laser beam passes through a calcite-prism polarizer, a water-filled Faraday cell, a heated bismuth cell, and a second polarizer crossed with the first; and then enters a silicon *p-i-n* photodiode detector. Light reflected from the front surface of the second polarizer is detected as a reference signal to divide out intensity variations. Both Nicol and Glan-Thompson polarizers have been used.

The Faraday cell produces a sinusoidal rotation of the plane of polarization with a frequency of 1 kHz and an amplitude of about 10^{-3} rad. Any rotation of the plane of polarization in the bismuth cell is measured by phase-sensitive detection (PSD) of the 1-kHz component from the signal detector. The PSD output, together with other signals for use in the analysis, is stored in a PDP-

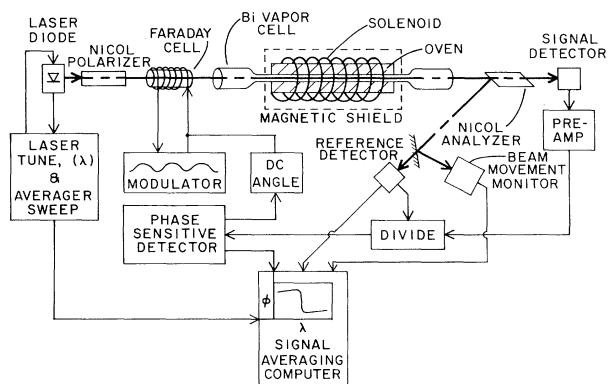


FIG. 1. Schematic view of the apparatus.

8/I computer as a function of laser wavelength.

The bismuth cell is an alumina tube with 1 m of its length heated to the desired temperature between 1200 and 1500 °K. Helium gas is used to confine the bismuth vapor to the heated part of tube. A solenoid wound around the tube provides a uniform magnetic field to control the Faraday rotation φ_F associated with the bismuth absorption line. Two concentric cylinders of Permalloy magnetic shielding surround the oven to exclude external fields.

Our tunable light source is a cw gallium-aluminum-arsenide laser diode, rather than the multi-mode parametric oscillator (OPO) used in our earlier work. The useful PNC data has come from two transverse-junction-stripe (TJS) diodes and one channeled-substrate-planar (CSP) diode.¹² We operate with a laser intensity between 2 and 10 mW, with about 95% of the light on a single mode set at the 8757-Å line, and the rest of the light mainly on modes far outside the hyperfine structure of the line. The Hitachi CSP laser shows a particularly clean spectrum near the main mode, and a linewidth <15 MHz. In this experiment, the wavelength of the laser is swept by varying the diode current.

The bismuth 8757-Å line is split into nine prominent magnetic-dipole hyperfine components. Figure 2 shows theoretical and experimental absorption, Faraday rotation, and PNC rotation curves. The theoretical curves are amended for the presence of light not on the main laser mode, and include Doppler broadening and a small measured collisional broadening.

Data are collected by sweeping the laser wavelength back and forth over part or all of the Bi absorption pattern. Data from the two sweep directions are stored separately. PNC data are ta-

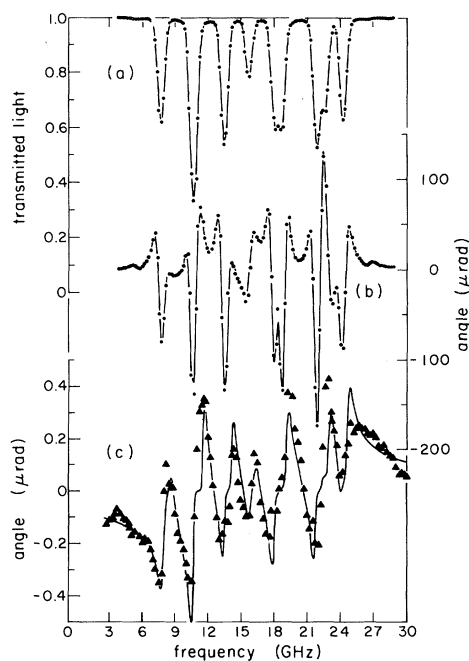


FIG. 2. Theoretical curves (lines) fitted to experimental data (points) for (a) absorption, (b) φ_F at 0.18 G, (c) φ_{PNC} at relative optical depths of 1, 1, and 10, respectively. The theoretical curves for φ_F and φ_{PNC} take into account dilution by off-mode laser light.

ken on alternate sweep periods, when the solenoid current is switched to a setting that minimizes φ_F and the oven heater current is switched off. The reference-beam signal is recorded to give an absorption curve. Faraday data are taken during the remaining sweep periods, when the oven heater current is switched on, and the solenoid current switched to give a large φ_F pattern. During all sweeps, potential sources of systematic error are monitored, and the signals stored in the computer. A single data set is completed after 20 min of running time. Depending upon the sweep rate, a data set contains between 300 and 1000 sweeps of both PNC and Faraday data. Data sets are taken with different optics, polarizer orientations, residual magnetic fields, buffer-gas pressures, and bismuth vapor densities.

Theoretical absorption, Faraday, and PNC curves are fitted to the corresponding experimental data in each data set. Variables in the PNC data fit include φ_{PNC} , φ_F for residual magnetic fields, and terms linear and quadratic in wavelength for optical interference effects. The fit program is checked on sample curves to ensure that no false φ_{PNC} is generated. The absorption

TABLE I. PNC optical rotation measured in this laboratory on the Bi 8757-Å line. Errors include systematic uncertainties, except when numbers are enclosed in parentheses. The data collection periods are listed in chronological order.

Data collection periods	Laser	$10^8 R$
A ^a	OPO	(-8 ± 3)
B ^b	OPO	(-0.7 ± 3.2)
C ^c	TJS-1	(-2.4 ± 1.4)
I ^c	TJS-2	-10.2 ± 3.1
II ^c	TJS-3	-11.8 ± 3.9
III ^c	TJS-3	-9.8 ± 2.4
IV ^d	CSP-1	-9.7 ± 2.5
V ^d	CSP-1	-10.8 ± 1.9
Weighted average (entries I-V only)		-10.4 ± 1.7

^aRef. 5.^bRef. 6.^cRef. 13.^dPresent experiment.

and Faraday data provide two independent measures of $(\eta - 1)l$, the optical depth. The φ_{PNC} fit and the optical depth yield a value of R for each experimental curve.

A collection of PNC data from twenty data sets taken in data collection period IV is shown in Fig. 2(c), and compared with the best fit by the φ_{PNC} theory curve. The evident asymmetry about each hyperfine component occurs in all data collected in the present experiment.

An analysis that makes use of all information collected with each data set seeks to find any correlations between the measured values of R and changes in each of the experimental conditions. This procedure is used to set limits on known sources of systematic error, and initially helped to uncover some of them. A discussion of the systematic controls and of other experimental details will be published soon.

A list of all measurements of R carried out in this laboratory is given in Table I. This table includes the first three measurements (A-C), made without the present systematic checks and controls. These measurements are not included in our final result. The remaining five measurements (I-V), each containing between 50 and 100 data sets and each taken under a broad range of conditions, are seen to yield a common value of R to within the quoted uncertainties. We use the five measurements to obtain our final experimental value, $R = (-10.4 \pm 1.7) \times 10^{-8}$, where the quoted error is predominantly systematic.

In Table II, we present recent results of atomic calculations of R based on the Weinberg-Salam

TABLE II. Calculations of R for Bi 8757-Å line with use of Weinberg-Salam theory ($\sin^2\theta_W = 0.23$). The last three entries go beyond the independent-particle model (IPM).

Calculation	$10^8 R$
Central-field IPM ^{a,b}	-17
Hartree-Fock IPM ^c	-16
Semiempirical ^d	-13
Parametric potential with shielding and first order ^b	-11
Hartree-Fock with shielding and first order ^e	-8

^aRef. 14.^bRef. 15.^cRef. 16.^dRef. 17.^eRef. 18.

theory. The earliest published central-field values¹⁴ of R were about twice the central-field value shown in the first entry. The change is due to a new experimental value of $\sin^2\theta_W$, and to improved calculations. The semiempirical value¹⁷ shown in Table II utilizes empirical data to include effects not contained in the central-field independent-particle model. The last two entries^{15,18} represent the most complete calculations made to date. There is approximate agreement between our experimental result and the three calculations that go beyond the independent-particle models.

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Selective Electron Capture: A Dominant Production Process for Few-Electron States of Light Target Atoms after Heavy-Ion Impact

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The total and delayed K -Auger-electron emission of Ne, N₂, and SF₆ targets was investigated after 1.4-MeV/u Kr¹⁸⁺ and Ar¹²⁺ impact. The lines of promptly decaying $1s2lnl'$ ($n \geq 3$) states observed nanoseconds after projectile impact demonstrate that selective electron capture from neutral target atoms into outer-shell orbitals of slow recoils is an important production mechanism for certain states in highly stripped target atoms. Contributions of prompt and delayed excited states are observed as well as specific cascades to inner-shell states.

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Spectroscopic studies of highly stripped slow target recoil ions after heavy-ion impact are of interest both for atomic physics and for aspects of plasma physics¹ and astrophysics,² as they give information on interactions of the highly charged ions with the surroundings. The target K -x-ray and K -Auger-electron spectra reflect the states that are directly excited by the heavy-ion impact, and when the target ionization is very high, lines produced by electron capture from neutral target particles into the recoiling target ions may occur.

Some evidence that electron capture in a second collision is responsible for specific lines in the observed K spectra was already found.³

Here, we report on the first direct observation of target K Auger electrons, which arise from capture collisions nanoseconds after the projectile impact. It is demonstrated that mainly lines from selective electron capture (SEC) dominate the spectra. A strong production of metastable K -hole configurations which survive capture collisions and populate specific outer-shell states is