Parity-Nonconserving Optical Rotation in Atomic Lead

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(Received 23 September 1983)

The search for parity nonconservation in heavy elements has been extended to the 1.28-μm $^3P_0 \rightarrow {}^3P_1$ magnetic dipole transition in atomic lead. The experimental result, $R = \mathrm{Im}(E1/M1) = (-9.9 \pm 2.5)\times 10^{-8}$, agrees, within the present uncertainties in experiment and atomic theory, with the prediction, $R = -13\times 10^{-8}$, derived from the Weinberg-Salam-Glashow theory of weak neutral-current interactions.

PACS numbers: 32.30.Bv, 11.30.Er, 12.30.Cx

We report here the observation and measurement of a violation of parity conservation in atomic lead, accomplished by studying optical rotation at the 1.28-μm magnetic dipole absorption line in lead vapor. Our results agree with atomic calculations[1,2] based[3] on the standard electroweak theory developed by Glashow,[4] Weinberg,[5] and Salam.[6] Parity nonconservation (PNC) has been reported on the 0.876-μm[7,8] and 0.648-μm[8-10] lines in bismuth (although discrepancies remain at 0.648 μm), the 0.293-μm line[11] in thallium, and most recently, the 0.539-μm line[12] in cesium. Our lead measurement contributes further to the clearing up of earlier uncertainties[13] concerning atomic PNC, to the establishing of the mutual consistency of the atomic calculations in different elements,[13] and to the setting of more precise limits on certain proposed modifications of the standard electroweak theory to which atomic PNC is particularly sensitive (such as the possibility of a second Z_0 neutral boson[14,15]).

Optical rotation experiments measure a quantity $R = \mathrm{Im}(E1/M1)$, where $M1$ is the magnetic dipole amplitude of the associated absorption line and $E1$ is the PNC-induced electric dipole amplitude. In a magnetic dipole transition, both the initial and final electronic states normally have the same parity and $E1$ is zero. The PNC interaction of the electrons with the nucleons causes a slight mixing of opposite parity states into both the initial and final states allowing for a small $E1$ in addition to $M1$. The two dipoles combine to produce a rotation of the plane of polarization of light by an angle $\varphi_{\mathrm{PNC}} = -4\pi l \lambda^{-1}(n-1)R$, where n is the index of refraction due to the magnetic dipole line, λ is the wavelength, and l is the path length. The PNC rotation therefore has the sharp dispersive behavior associated with the index of refraction at the absorption line to distinguish it from background effects. The size of the change in φ_{PNC} at the 1.28-μm absorption line in lead vapor is about 10^{-7} rad for one absorption length.

The experimental apparatus has been converted from the one used for our earlier measurements on the 0.876-μm line in atomic bismuth. At that wavelength, we used GaAlAs diode lasers, whereas in the present experiment we use a somewhat similar InGaAsP diode laser, kindly supplied by Fujitsu Laboratories Ltd.,[16] that operates at 1.278 μm.

Figure 1 shows the experimental arrangement. The laser light is sent through a calcite polarizer, followed by a toluene Faraday cell where the plane of polarization is sinusoidally modulated by 10^{-3} rad at 1 kHz. The light then enters a magnetically shielded vapor cell heated to between 1200 and 1500 K to produce a 1-m column of lead vapor at pressures up to 20 torr. Finally, the polarization of the light is analyzed by a second polarizer turned 90° with respect to the first and detected by a liquid-nitrogen–cooled Ge p-i-n diode. A reflection from the front face of the analyzer is sent into a reference detector. The two signals are divided to substantially reduce intensity variations and analyzed in a phase-sensitive detector at the 1-kHz Faraday modulation frequency to provide an output linear in angle of rotation between the polarizers while providing

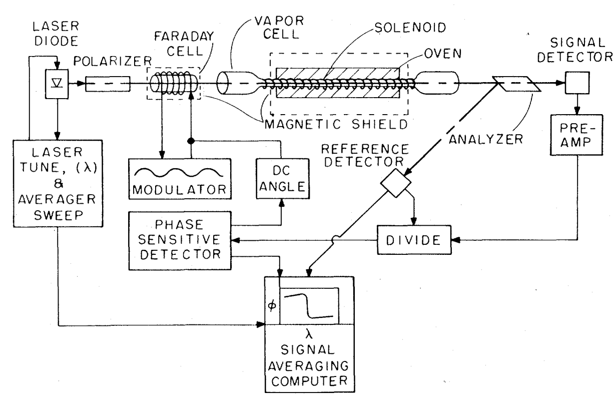

FIG. 1. Schematic view of the apparatus.

further rejection of intensity changes. This pure rotation signal is stored in a PDP-8/I computer as a function of laser wavelength and analyzed for the characteristic PNC rotation with its sharp asymmetry about each absorption component, as displayed in Fig. 2(c).

The laser wavelength is swept back and forth across the absorption line at $\frac{1}{3}$ Hz with a triangle wave form. A solenoid around the vapor cell is switched between high and low current on alternate sweeps. The magnetic field generated by the solenoid in the high-current position causes a known Faraday rotation in the lead vapor that is used to calibrate the rotation angle sensitivity. The low current cancels residual axial magnetic fields inside the shield while the PNC rotation is measured. Typically, an uninterrupted data run comprises 150 sweeps of each type, taking 15 min. The polarizers are then rotated 180° and the optics completely realigned before

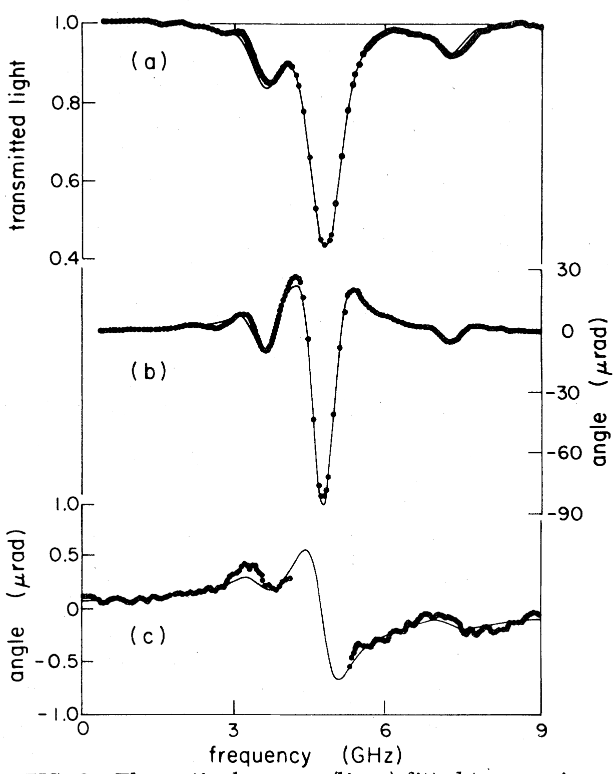

FIG. 2. Theoretical curves (lines) fitted to experimental data (points) for (a) absorption, (b) Faraday rotation at 30 mG, and (c) φ_{PNC} for the first data group of Table I. The relative optical depths are 1, 1, and 8.5, respectively. The curves for Faraday and PNC take into account dilution by off-mode laser light. No data are shown on resonance for PNC because of nearly total absorption of light there.

the next 15-min data run. This procedure is repeated over several days to accumulate a data group. There are six data groups in all, each containing between 15 and 70 data runs, and each taken with a different lead vapor density and one of two polarizer types, Glan-Thompson (GT) or Nicol (N).

We use naturally occurring lead for our experiment. The even isotopes have no hyperfine structure and negligible isotope shift. The odd isotope of relative abundance 24% has a nuclear spin of $\frac{1}{2}$ which splits the 1.28-μm line into two hyperfine components, one on each side of the even-isotope line. There is no background absorption spectrum from lead molecules or other sources. Figure 2(a) shows the measured absorption and a theoretical best-fit curve for an optical depth of about 1 on the even-isotope line. Figure 2(b) shows the Faraday data and theoretical curve for a 30-mG field. Figure 2(c) shows the PNC data and theoretical curve for the first data group.

Shot noise in the laser photons and noise within the detector are both negligible in this experiment compared with fluctuations in the data caused by polarizer imperfections. A background rotation pattern φ_B, in which the variation of angle with wavelength is due to interference among scattered beams from imperfections within the polarizers, causes a variation in the φ_{PNC} measurement from run to run. The size and sign of φ_B change completely with minor reorientations of the polarizers, and also change in time, averaging to zero over many runs. The net size of φ_B that remains after averaging throughout a data group is estimated from the rotation signal in the wings of the line and is included in the estimated error for that group. We obtain additional protection against such a systematic error by running different data groups with different polarizers and at different optical depths, the latter procedure varying the ratio of φ_{PNC} to φ_B by a factor of 10.

Another major difficulty is that the InGaAsP laser, although excellent for a prototype optical device in this wavelength region, is not completely monochromatic. The linewidth of the main mode is about 200 MHz, there are satellite modes about 1 to 2 GHz on either side of the main mode with 5% of the power in each, and about 20% of the power is on different longitudinal modes over 100 GHz away from the main mode. We have tested for possible systematic errors caused by this output spectrum. The most important error arises from the finite width of the main laser mode, which couples with any slope $d\varphi/d\lambda$ in the

TABLE I. PNC value obtained for individual data groups listed chronologically.

Optical depth	Polarizers	R Value (10^{-8})	Stat. error (10^{-8})	Sys. error (10^{-8})
8.5	GT	-15.54	4.0	2.6
50	GT	-9.05	1.3	1.5
8.0	N	-2.78	8.1	3.9
25	N	-10.03	2.8	1.9
75	N	-11.53	3.0	1.6
15	GT	-8.33	3.6	2.5
Wt. Av.		-9.9 ± 2.5[a]		

[a]Some systematic errors are random between data groups while others are not. This final error takes this into consideration.

background angle to yield an asymmetrical rotation angle about the absorption line that projects onto φ_{PNC}. The size of this projection can be calculated, and is within the limits set experimentally by observed correlations between φ_{PNC} and $d\varphi/d\lambda$. An upper limit to the effect is set by the average angle slope in each data group and is included in the estimated error.

It is encouraging to note that the lasers initially used in the bismuth experiment had output spectra similar to the laser discussed here. The results obtained at that time agreed to within the 15% quoted accuracy with those later obtained with improved[17] lasers, which were a factor of 10 better in each of the spectral characteristics mentioned above.

Table I gives the results of our six data sets and the statistical and systematic error associated with each. The statistical error is a measure of the spread of the individual runs for each data group. The systematic error, different for each data group, shows the measured sensitivity to the known possible systematic effects. In general, the errors decrease as the absorption increases. We sum both statistical and systematic errors to obtain a weighted average of all data groups, and obtain the final value

$$R=(-9.9\pm2.5)\times10^{-8},$$

in which the error includes the statistical and systematic contributions.

To date, two theoretical numbers for the size

TABLE II. Comparison of the predicted and measured results of the atomic experiments. Theoretical values are averaged from those atomic calculations that include the major corrections to the central-field-independent particle model. We omit errors from the theoretical values because many calculations are published without error estimates. The Weinberg-Salam theory is assumed, with $\sin^2\theta_W=0.215$, the current best value for atomic experiments when radiative corrections are taken into account.[(a)]

Atomic transition (μm)	Measured quantity	Experimental value	Theoretical value	Ratio Expt./Theory
Bi 0.876	$E1_{\mathrm{PNC}}/M1$	$(-10.5\pm1.3)\times10^{-8}$ (b)	-11×10^{-8} (c)	1.0
Bi 0.648	$E1_{\mathrm{PNC}}/M1$	-10×10^{-8} (d)	-13×10^{-8} (c)	0.8
Pb 1.279	$E1_{\mathrm{PNC}}/M1$	$(-9.9\pm2.5)\times10^{-8}$ (e)	-13×10^{-8} (f)	0.8
Tl 0.293	$E1_{\mathrm{PNC}}/M1$	$(2.8^{+1.0}_{-0.9})\times10^{-3}$ (g)	1.7×10^{-3} (h)	1.6
Cs 0.539	$E1_{\mathrm{PNC}}/\beta$	$-1.34\pm0.22\pm0.11$ mV/cm (i)	-1.7 mV/cm (j)	0.8

[a]Ref. 7.
[b]Refs. 8–10. (Here we quote, without including errors, the average value for the different 0.648-μm experiments, which remain mutually inconsistent.)
[c]This work.
[d]Ref. 11.
[e]Ref. 12.
[f]Refs. 1, 19, and 20.
[g]Refs. 1 and 2.
[h]Ref. 21.
[i]Ref. 22.
[j]Ref. 18.

of the effect in lead have been published. They are a semiempirical value[1] of $R = -11 \times 10^{-8}$ and a relativistic Hartree-Fock value[2] of $R = -14 \times 10^{-8}$, both using $\sin^2\theta_W = 0.215$.[18] We average the two numbers, obtaining

$$R = -13 \times 10^{-8}.$$

The experimental and theoretical values agree within their respective uncertainties.

Table II compares the most recent predicted and measured results of all atomic PNC experiments, including the present one. Better diode lasers in the 1.3-μm wavelength region will improve the accuracy of the lead experiment and will make possible an experiment on the thallium absorption line at 1.283 μm. Work done on placing diodes in external cavities to improve their spectral properties[23] is being explored. Finally, improved polarizers are being studied to reduce errors further.

We would like to thank Jack Hollister who did some of the initial work for this experiment. This work is supported by the National Science Foundation through Grant No. PHY-8203512.

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