Parity nonconservation in atomic bismuth

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(Submitted April 2, 1980)
Pis'ma Zh. Eksp. Teor. Fiz. **31**, No. 9, 556–560 (5 May 1980)

The results of new experiments in search of parity nonconservation in a Bi atom are reported. Like in Ref. 1, the theoretically predicted parity nonconservation was not observed in the experiment.

PACS numbers: 32.90. + a

In a previous paper we reported the results of an experiment in search of optical activity of Bi vapors due to a weak parity-nonconserving interaction of atomic electrons with the nucleus (this effect, which was predicted by the Weinberg-Salam model of weak interactions, henceforth will be called the PNC effect). The measurements were made using the $F = 6 \rightarrow F = 7$ component of the hyperfine structure of the $6P^3$, $^4S_{3/2} - {}^2D_{5/2}$ magnetic dipole transition, $\lambda = 648$ nm. According to Refs. 2–5, the parameter $R = \mathrm{Im}(E_1/M_1)$, where E_1 is the matrix element of the electric dipole produced because of the PNC effect and M_1 is the matrix element of the magnetic dipole, was assumed to be equal to $R_{\mathrm{theor}} = -18 \times 10^{-8}$.[1] The experimental value obtained in Ref. 1 is

$$R_{\mathrm{exp.}} = (-0.02 \pm 0.1)\, R_{\mathrm{theor.}} \tag{1}$$

See Refs. 6–11 for other, previously performed experiments in search of parity nonconservation in atomic bismuth.

This paper presents the results of new experiments of the same transition of a Bi atom. The measurements were made by using the same method as that in Ref. 1. In one cycle we measured the rotation angles ϕ at three spectral points—the maximum ω_0

 0021-3640/80/090522-05$00.60

of the absorption contour and the zeros of the Faraday rotation ω_- and ω_+, which almost coincide with the maximum and minimum of the $\phi_{PNC}(\omega)$ curve. In this way we determined the complete scope of the PNC effect.

This value is related to the theoretical characteristic $R = \mathrm{Im}(E_1/M_1)$ of the transition by the relation

$$\Delta\phi^{\mathrm{theor}}_{\mathrm{PNC}} \approx -\kappa L R, \tag{2}$$

where κ is the maximum absorption coefficient and L is the optical path length in a bismuth vapor (κL is the optical thickness). Like in Ref. 1, one series of measurements contained 50 cycles.

During the measurements we tried to average out the possible interference effects in the polarimeter. All the measurements were performed using piezoceramics on which the polarizer and analyzer were placed; their positions were modulated in two mutually perpendicular directions—along the light beam and perpendicular to it. The Faraday modulator was temperature-controlled. The single-mode lightguide, which provided a stable intensity distribution at the polarimeter's entrance regardless of the intensity redistribution in the laser beam, was replaced by a longer one (13-m lightguide instead of the 0.7 m was used in Ref. 1). In the second experiment (the first experiment was performed in Ref. 1) we performed four series of measurements at $\kappa L = 0.8$ and $\Delta\phi^{\mathrm{theor}}_{\mathrm{PNC}} = 15 \times 10^{-8}$ and three series at $\kappa L = 1.0$ and $\Delta\phi^{\mathrm{theor}}_{\mathrm{PNC}} = 18 \times 10^{-8}$. Before the start of the measurements we ran one control series of measurements at a reduced temperature, when the maximum absorption was reduced by a factor of ten. After completing the seven series of bismuth measurements, we performed control measurements of the Faraday rotation ϕ_F on the molecular line in Fig. 1. The Faraday rotation constant for this line is considerably smaller than that for the atomic line. The

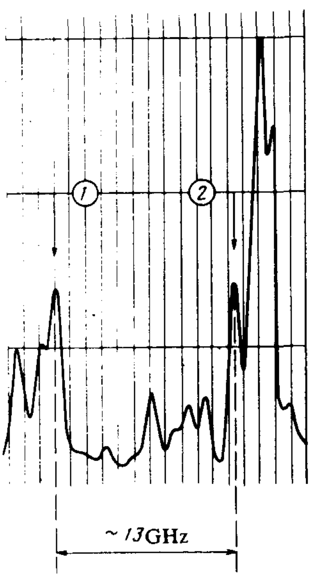

FIG. 1. Absorption spectrum of bismuth vapors: 1, $F=6 \rightarrow F=7$ Bi line; 2, molecular control line.

measurements were made at three spectral points ω_0, ω', and ω'', where ω_0 is the maximum of the absorption contour, and the differences $\omega_0 - \omega'$ and $\omega_0 - \omega''$ are the same as the differences $\omega_0 - \omega_-$ and $\omega_0 - \omega_+$ for the atomic line. Calibration of the effect was done in a field $H = 100$ mG and $H = -36$ mG. Since ϕ_F is linear with respect to H, we determined the values of the field H, for which $(\phi''_F - \phi'_F) = 7 \times 10^{-8}$ rad and $(\phi''_F - \phi'_F) = 25 \times 10^{-8}$ rad, respectively. Four series of measurements were made using the first value of H and one series using the second. The results of these measurements are shown in Fig. 2. For the seven series of measurements using the atomic bismuth line the value of R, which was determined from the measured value of $\Delta\phi_{\rm PNC}$, was

$$R_{\rm exp} = (+0.22 \pm 0.1)\, R_{\rm theor}. \tag{3}$$

For the four control series of measurements

$$(\phi''_F - \phi'_F)_{\rm calc} = (7 \pm 5)\times 10^{-8};\ (\phi''_F - \phi'_F)_{\rm exp} = (8.3 \pm 1.8)\times 10^{-8}. \tag{4}$$

For the last control series

$$(\phi''_F - \phi'_F)_{\rm calc} = (25 \pm 7)\times 10^{-8};\ (\phi''_F - \phi'_F)_{\rm exp} = (30.5 \pm 4.8)\times 10^{-8} \tag{5}$$

The comparatively large uncertainty in the expected values of $(\phi''_F - \phi'_F)$ in Eqs. (3) and (4) is due to the fact that the calibration of the Faraday effect at the field values $H = 100$ mG and $H = -36$ mG was done using shortened series of measurements containing only 20 cycles. As can be seen, the predicted (specified) rotation values are in good agreement with the measured values.

In the third experiment we performed four series of measurements of the PNC effect for $\kappa L = 0.9$ and $\Delta\phi^{\rm theor}_{\rm PNC} = 16 \times 10^{-8}$ and three control series at a reduced bismuth vapor density of $\kappa L = 0.2$. As a result, we obtained

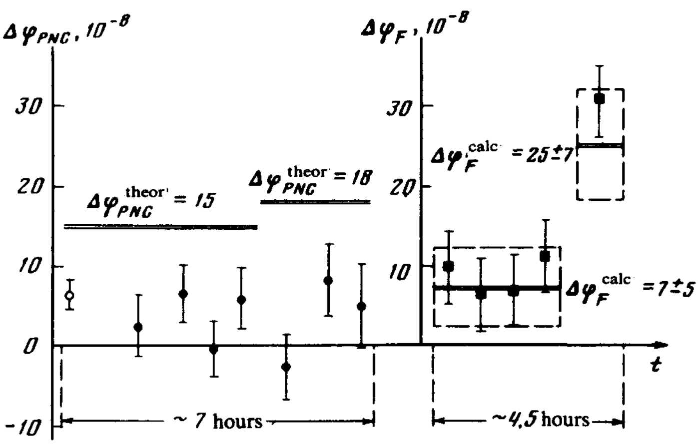

FIG. 2. Results of measurements in second experiment: ●,—measurements on $F = 6 \to F = 7$ line of atomic bismuth; ○,—control measurements at reduced bismuth pressure; ■,—control measurements of $\Delta\phi_F = (\phi''_F - \phi'_F)$ on the molecular line.

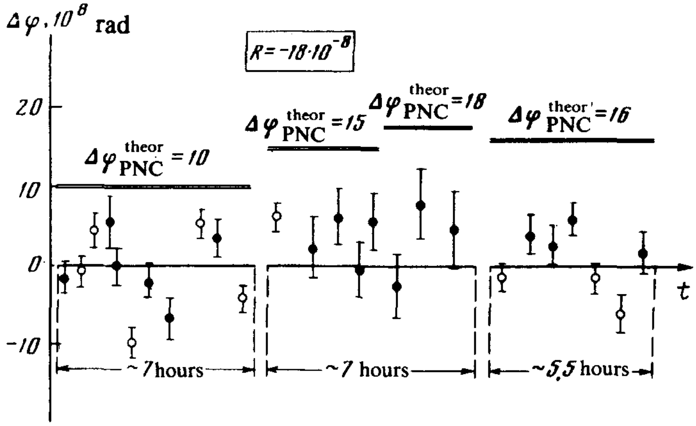

FIG. 3. Combined results of $\Delta\phi_{PNC}$ measurements: •,—measurements on the $F=6\rightarrow F=7$ atomic bismuth line; ∘,—control measurements at reduced bismuth pressure.

$$R_{exp} = (+0.23 \pm 0.08)\, R_{theor} \tag{6}$$

The alternating sequence of the primary and control series of measurements is shown in Fig. 3, in which we have assembled all 17 series of measurements of the PNC effect and the nine control series that were performed in all three experiments.

In Fig. 3 the error is indicated as $\pm$ one standard deviation $S_{\overline{\Delta\phi}}$ for the $\Delta\phi_{PNC}$ value averaged over a given series. A typical value of $S_{\overline{\Delta\phi}} \approx (2.5-3.5)\times 10^{-8}$ is close to the minimum limiting value determined by the shot noise (the intensity of the beam in front of the analyzer was $I \sim 0.3\times 10^{15}$ photons/sec, the quantum efficiency of the detector was $\eta \sim 0.05$, the storage time per cycle was $T=5$ sec, and the number of cycles was $n=50$). Moreover, the spread of the average values of $\Delta\phi_{PNC}$ within individual series, which markedly exceeds $S_{\overline{\Delta\phi}}$ in some cases, indicates that there are additional instrumental errors that vary comparatively slowly with time. Their contribution to the total measurement error can be estimated by taking the average value of $\Delta\phi_{PNC}$ in each series as an independent measurement and computing the corresponding standard deviation value S' from the spread of these values. Such a procedure was used to calculate the average value $\langle R_{exp}\rangle$ for all 17 series of measurements. The corresponding standard deviation for $\langle R_{exp}\rangle$ is equal to $S' = 1.2\times 10^{-8}$. An estimate of this value as a result of averaging over all 850 cycles gives $S'' = 0.5\times 10^{-8}$. The difference between S' and S'' also indicates that additional instrumental errors are present in the measurements in addition to shot-noise errors. Since $S' > S''$, They play the major role. Because of this, we assume that the value $S = [(S')^2 + (S'')^2]^{1/2} \approx 1.3\times 10^{-8}$ is the estimated standard deviation for $\langle R_{exp}\rangle$. For all 17 series of measurements of the PNC effect this gives

$$\langle R_{exp}\rangle = (+0.13 \pm 0.07)\, R_{theor}. \tag{7}$$

Analogously, for all nine control series we obtain

$$\Delta\phi'_{PNC} = (-0.87 \pm 1.8)\times 10^{-8}. \tag{8}$$

We note that in Eqs. (1), (2), and (5) $\pm$ one standard deviation is the error for the average value of R_{exp}/R_{theor} over the total number of cycles of a given experiment, i.e., a value like S''.

It follows from Eq. (6) that our experimental results, which clearly contradict the theoretical predictions, are inconsistent with the predicted value of $R_{theor} \approx -18 \times 10^{-8}$, although they do not exclude the possibility that an effect with $R < 0.25\ R_{theor}$ exists. We cannot be more specific at this stage of the experiment. At present, we are working to reduce the instrumental errors of our facility.

We wish to thank N. G. Basov and M. A. Markov for their support of this work.

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