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Translated by Julian B. Barbour

Parity nonconservation in bismuth atoms and neutral weak-interaction currents

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(Submitted 11 March 1980)

Zh. Eksp. Teor. Fiz. 79, 713–729 (September 1980)

Results are presented of measurements of the natural optical activity of atomic bismuth vapor in the region of the $M1$ transition $^4S_{3/2}$–$^2D_{5/2}$ at $\lambda = 648$ nm. The measured value of the circular polarization $P = -2R = -2\,\mathrm{Im}\,[A(E1)/(M1)] = (40.4 \pm 5.4) \times 10^{-8}$ agrees with the results of the calculations performed within the framework of the Weinberg-Salam method with $\sin^2\theta = 0.25$.

PACS numbers: 32.30.Jc, 11.30.Er

Following the discovery of neutral currents in weak interactions between neutrinos and nucleons,[1–3] the interest in weak-interaction gauge theories, which had predicted the existence of these interactions, has increased, and the problem of the existence of an analogous interaction between electrons and nucleons has become vital. As early as in 1959, Zel'dovich[4] has indicated that the weak interaction of electrons with nucleons can lead to parity nonconservation in atoms. The parity-nonconserving interaction of electrons with nucleons leads to a mixing of levels of opposite parity in atoms. It can be shown[5] that the spatial distribution of the electron spin in the atom has in this case a spiral structure, which in turn leads to a difference between the interaction of right- and left-polarized photons with the atoms and, as a consequence, to circular polarization of the radiation and to natural optical activity of matter in the atomic state.

An important step towards real experiments aimed at a search for this interaction was made by M. Bouchiat and C. Bouchiat,[6] who called attention to the enhancement of the parity-nonconservation effects in heavy atoms, and proposed an experiment for the measurement of circular polarization in the strongly forbidden magneto-dipole transition in cesium. This was soon followed by a number of suggestions[7–9] of studying the natural optical activity of vapors of heavy metals near the normal magnetodipole transitions.

It is known[10] that the parity-violating weak interaction of electrons with nucleons leads to the appearance of P-odd correlations of the form $\sigma\cdot\mathbf{p}$, $\sigma_N\cdot\mathbf{p}$, and $\sigma_N \times \sigma\cdot\mathbf{p}$ where σ and $\mathbf{p}$ are the spin and momentum of the electron, and σ_N is the spin of the neutron or proton. In heavy atoms, the parity-nonconservation effects due to the correlation of the electron spin with its momentum are Z times larger than the effects due to correlation of the spin of the nucleon with the electron momentum, since the latter are determined only by nucleons with unpaired spins.

We present below the results of an experimental search for a parity-nonconserving weak interaction between electrons and nucleons, initiated by us in 1974 under the influence of discussions with I. B. Khriplovich at our Institute.

We chose for the investigation the red bismuth line $\lambda = 648$ nm; we started from the fact that this line can be obtained from the dependable tunable cw dye laser with a sufficiently narrow line. A shortcoming of this transition is that it lies in a region overlapped by the rather dense spectrum of molecular bismuth (the partial vapor pressures of atomic and molecular bismuth are approximately equal).

The ground state of the bismuth atom pertains to the configuration $6p^3$, i.e., it has three outer p electrons in excess of the filled shells. Normal $M1$ transitions are

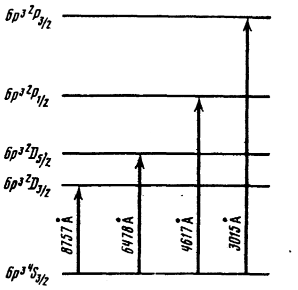

FIG. 1. Scheme of $M1$ transitions of atomic bismuth.

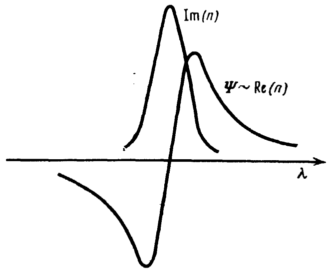

FIG. 2. Expected dependence of the angle of rotation of the plane of polarization and of light absorption on the wavelength in the region of the $M1$ transition.

possible only between levels belonging to one electron configuration. The scheme of such transitions from the ground state of bismuth is shown in Fig. 1. The degree of circular polarization of the radiation in these transitions, calculated within the framework of the model of Weinberg[11] and Salam[12] with the free parameter of this model $\sin^2\theta = 0.25$, are listed in Table I. Since only the Novosibirsk group of theoreticians cites an estimate of the calculation error (≤15–20%), the experimental results were subsequently compared with just their results.

To study the optical activity due to parity nonconservation, a frequency-modulation measurement technique was developed. In the proposed technique the wavelength of the light is modulated and effective use is made of the fact that the expected effect is proportional to the real part of the refractive index and takes the form of a dispersion curve (see Fig. 2) that changes drastically when the wavelength of the light goes through resonance.

Just as in the ordinary measurement schemes, the cell with the bismuth vapor is placed between the polarizer and the analyzer. When the wavelength is scanned symmetrically relative to the center of the absorption line, the intensity of the light passing through the analyzer

$$I' = I(t)\left[\sin^2(\theta + \Psi_{PNC}(t)) + \varepsilon^2\right] \approx I(t)\theta^2(1 + 2\Psi_{PNC}(t)/\theta + \varepsilon^2/\theta^2), \quad (1)$$

contains the first harmonic (more accurately, the odd harmonics) only in the case of parity nonconservation, inasmuch as in symmetrical scanning $I(t)$ contains only even harmonics of the modulation frequency. In the foregoing expression for the intensity, θ is the angle between the axes of the polarizer and analyzer, and ε^2 is the relative intensity of the transmitted light at $\theta = 0$. For small scanning amplitudes, the fundamental signal is proportional to $\partial\Psi_{PNC}/\partial\lambda$. Thus, in contrast to ordinary small-angle measurement schemes, one measures here in fact the derivatives of these angles with respect to the wavelength of the light.

TABLE I. Circular polarization in bismuth.

	λ, nm				
	876	648	462	301	Reference
$P\cdot 10^7$	2.9	3.8	6.5	8.3	[13, 14]
	3.6				[15]
	2.4	2.8			[16]

It was implied in the preceding reasoning that the angle θ between the axes of the polarizer and analyzer is small. To choose the optimal value of this angle, let us see how it affects the ratio of the useful signal to the noise. Assuming that the noise is purely statistical, and that the optical system is ideal, this ratio does not depend on the angle θ, inasmuch as both the useful signal $\sim I\theta\Psi$ and the statistical noise $\sim(I\theta^2)^{1/2}$ are proportional to θ. However, since the polarizer and analyzer are not perfect, the relative intensity of the light passing through them amounts to $\varepsilon^2 \sim 10^{-7}$ at $\theta = 0$. Therefore the use of angles θ smaller than ε affects adversely the ratio of the useful signal to the noise. At the same time, at angles θ larger than ε, the relative magnitude of the useful signal in the measuring channel decreases, and this imposes more stringent requirements on the electronics and on the permissible values of the various false effects. With this in mind, we used angles θ in the interval from 10^{-3} to 4×10^{-3} rad.

The experimental setup used to measure the optical activity of the bismuth vapor is shown in Fig. 3. The light source was a Model 375 Spectra Physics tunable dye laser. This laser model has an approximate line width 0.1 Å and does not permit rapid scanning of the wavelength. To use the proposed procedure it was necessary to tune the laser wavelength rapidly and to have a much narrower line width. To this end, a new method of selecting the longitudinal modes of the laser was proposed and realized.[17] An additional element was introduced into the laser, namely a selector, which

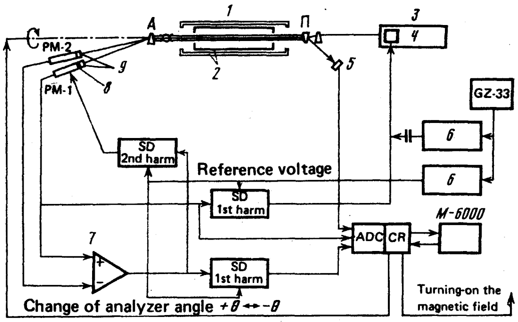

FIG. 3. Diagram of experiment: 1—oven and cell with Bi vapor, 2—magnetic screens, 3—laser, 4—selector, 5—photodiode, 6—attentuators, 7—subtraction circuit, 8—filter, 9—diffusors, SD—synchronous detector, GZ-33—sound generator, CR—control register.

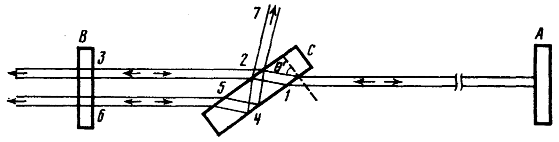

FIG. 4. Schematic representation of the position of the selector in the laser resonator: A, B—resonator mirrors, C—plane-parallel plate, 2—partly reflecting coating, 4—totally reflecting coating; for the remaining notation see the text.

ensured single-frequency tunable operation with an output power in the beam up to 15 mW. The selector was a plane-parallel plate with special coatings and was placed inside the laser resonator.

The operating principle of the selector is shown in Fig. 4. To decrease the light reflection from the sections 1 and 5 of the surface, the plate of the selector is placed at the Brewster angle to the resonator axis. The selector has two reflecting coatings on the surface sections 2 and 4. The plate splits the laser beam into two, one of which, after reflection from the exit mirror of the laser resonator at the point 3 and subsequently from the semitransparent coating 2, goes off partially in the direction 7. Going off in the same direction is also part of the light of the second beam, reflected at the point 6 of the resonator mirror. It is easily seen, that if the condition

$$4dn\cos\theta'=m\lambda \tag{2}$$

is satisfied (d is the plate thickness, n is the refractive index, θ' is the refraction angle, m is an integer, and λ is the wavelength of the radiation), destructive interference of the beams takes place, and no light goes from the resonator in the direction 7. In practice, the laser generates on that longitudinal mode for which condition (2) is best satisfied.

To tune the laser frequency, the selector is mounted on a piezoceramic in such a way that the angle of inclination is changed when a voltage is applied.

A selector having a plate 3 mm thick and additionally introduced into the laser made it possible to obtain single-frequency tunable-laser operation without a substantial change in the lasing threshold. Variation of the voltage on the piezoceramic from 0 to 100 V changed the frequency by 10 GHz, corresponding to 25 longitudinal modes of the laser resonator. The use of the selector made it possible to scan the radiation wavelength discretely in steps of ~0.006 Å, with a scanning frequency up to several kHz, and with amplitude up to 10 Doppler line widths. The actual scanning frequency used in the experiment was 1 kHz, and the amplitude was equal to one or two Doppler line widths. The light modulated in wavelength at a frequency 1 kHz passed through a polarizer, a cell with bismuth vapor, and an analyzer. The polarizer and analyzer were Iceland spar prisms with vertex angle 12°. The axes of the polarizer and the analyzer were mounted at an angle θ to each other. A special electromechanical system made it possible to reverse the sign of the angle θ.

The analyzer splits the beam into two beams with mutually orthogonal polarizations, one of which is weaker than the other by a factor θ^2. Each of these two beams was detected by an FÉU-79 photomultiplier (5% quantum yield at $\lambda=648$ nm). Special cavities for diffuse scattering of the light were placed in front of the photomultipliers. Without the cavities, the inhomogeneity of the photocathodes, together with the change of the structure and the shift of the laser beam, which occur when the wavelength is changed, leads to large false effects. To equalize partially the intensities, a gray filter with attenuation coefficient $\approx 10^3$ was placed in front of the photocathode of the photomultiplier that registered the bright beam.

The signals from the photomultipliers depend on θ and on Ψ_{PNC} in the following manner:

$$V_1(t)\propto I(t)\cos^2(\theta+\Psi_{PNC})\approx I(t), \tag{3a}$$

$$V_2(t)\propto I(t)\sin^2(\theta+\Psi_{PNC})\approx I(t)\theta^2(1+2\Psi_{PNC}/\theta). \tag{3b}$$

Since the signal from the photomultiplier PM-1 does not depend on the measured effect, it should contain only the even harmonics of the scanning frequency when the laser wavelength is scanned symmetrically with respect to the line center. Inasmuch as in the experiment the optical length of the bismuth vapor is equal to several absorption lengths, V_1 depends on the time very strongly. Therefore, in the case of inexact tuning to the absorption line center, the first harmonic of the scanning frequency appears in the signal V_1. Depending on the side on which the shift from the line center took place, the phase of the first harmonic of the signal is changed by 180°. The signal V_1 was synchronously detected at the first harmonic of the scanning frequency, amplified, and applied to the laser selector for automatic control of the wavelength. This feedback ensured the absence of the first harmonic from $I(t)$ at a level better than 10^{-3}.

The voltages on the photomultipliers were chosen such that the signals V_1 and V_2 were practically equal. These signals were fed to a subtraction circuit. When they are equal, the difference signal

$$V\propto I(t)\theta\frac{\partial\Psi_{PNC}}{\partial\lambda}$$

can contain the first harmonic of the scanning frequency only through the dependence of Ψ_{PNC} on the wavelength. Good subtraction of V_1 and V_2 was ensured because when they were unequal the signal V contained a large second harmonic of the scanning frequency, the phase of which depends on which of the signals, V_1 or V_2, is stronger. The difference signal was synchronously detected at the second harmonic of the scanning frequency and controlled the supply voltage to the photomultiplier PM-1. This feedback ensured a subtraction accuracy at a level better than 10^{-3}.

As a result of using the two feedback loops, the false first-harmonic signal should correspond to an effective rotation angle $2\Psi_{eff}/\theta\leq 10^{-6}$ [see formulas (3)], so that $\Psi_{eff}\lesssim 10^{-9}$ rad at the employed angles θ.

In the experiment, however, the level of the first harmonic in the difference signal V, as will be seen presently, was determined not by the electronics alone. For additional suppression of the false signals, the

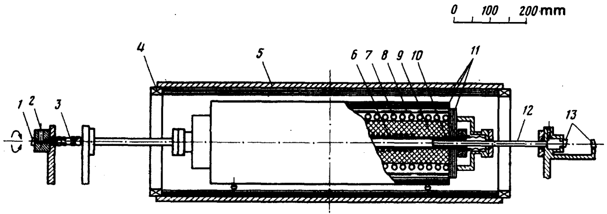

FIG. 5. Oven and cell with bismuth vapor: 1—analyzer prism, 2—entry of helium, 3—movable gasket, 4—coil, 5—steel housing, 6—heater, 7—cooling, 8—sectionalized coil, 9—thermal insulation, 10—ceramic cell, 11—magnetic screens, 12—collimators, 13—polarizer prism.

measurements were made alternately at two values ($+\theta$ and $-\theta$) of the reference angle. The difference of the mean values V_+ and V_- for these two cases served as a measure of the parity nonconservation. The rotation angle is defined as

$$\Psi_{\exp} = \frac{\partial \Psi_{PNC}}{\partial \lambda} \Delta\lambda$$

and is connected with the measurement results in the following manner:

$$4\Psi_{\exp}/\theta = (V_+ - V_-)/V_2 K, \qquad (4)$$

where K is the gain of the subtraction circuit and first-harmonic synchronous detector.

Bismuth vapor was produced with an oven whose construction is shown in Fig. 5. The oven operated on the heat-pipe principle. The cell with the bismuth vapor was connected to a large ballast volume filled with helium. When the oven was heated and the cell temperature reached a value such that the saturated bismuth vapor pressure became equal to the pressure of the helium in the system, the helium was forced out and only the bismuth vapor remained in the central part of the cell. In such a system, a change in the applied power changes not the temperature, and hence not the vapor pressure, but only the length of the region occupied by the vapor. The entrance and exit windows of the cell were the polarizer and analyzer prisms. The cold helium prevented the end faces of the cell from being sputtered with bismuth.

To prevent production of a constant magnetic field, which would lead to rotation of the plane of polarization and could imitate the parity-nonconservation effect, the heater was fed with 50 Hz alternating current. To make the alternating field in the system weak, the heater winding was bifilar. To suppress the external magnetic field, the oven with the cell was placed in a double magnetic shield of annealed Permalloy, so that the magnetic field at the central part of the cell was reduced to less than 2×10^{-5} G. The use of correcting coils placed on the ends of the outer screen made it possible to obtain a field of this value over a length up to 60 cm. In the construction of the apparatus, care was taken to avoid contacts between different metals, so as to prevent the appearance of magnetic fields due to the thermoelectric power produced when the oven is heated. The final criterion of the smallness of the residual field in the heated cell was the absence of magnetic rotation in the case of measurements on those atomic lines at which there is no Faraday rotation, and the effect due to the parity nonconservation is known to be absent. An additional coil consisting of seven sections was placed inside the screen and used to measure the distribution of the bismuth vapor density along the cell axis. To this end, by turning on the sections of the coil in succession, the Faraday rotation was measured for lines in which it was large.

The electronic circuitry includes a number of specially developed devices.[17] The synchronous-detector blocks in Fig. 3 contain narrow-band amplifiers for the frequencies 1043 (first harmonic) and 2086 Hz (second harmonic). During the first and most difficult stages of the experiment, frequent use was made of the provisions contained in the circuitry for discretely regulating the integration time of the synchronous detectors and the total gain of the useful first harmonic signal from photomultiplier PM-2.

In the last measurements we used an automatic control system for monitoring, gathering, and reducing the data, in the form of a CAMAC standard connected to an M-6000 computer. The first-harmonic synchronous-detector signal, proportional to the measured effect, and the intensities of the incident and transmitted light were entered into the computer memory through amplitude-digital-converter (ADC) blocks. A special fast ADC block[18] recorded the information on the absorption line shape. A controlled-relay block reversed, in accordance with the program, the analyzer prism angles $+\theta$ and $-\theta$, and controlled the system that changed by 180°, in synchronism with the reversal of the angle θ, the phase of the supply of the heating element of the oven. The heater phase was reversed for the following reasons. The heating element produced a small alternating magnetic field of 50 Hz frequency along the axis of the cell with the bismuth vapor. The carrier frequency 1 kHz was also subject to slight modulation at 50 Hz. As a result, this alternating rotation of the bismuth vapor can produce a false signal. Special measures were taken to detect and suppress this induced noise. Since the useful signal was the difference between the first harmonics at the reference angle positions $+\theta$ and $-\theta$, synchronous reversal of the heater supply phase and of the angle θ automatically ensures subtraction of this induced noise.

The program made it possible to operate in a mode in which the parity nonconservation effect and the Faraday rotation could be measured. The programs were started and the necessary parameter introduced from a videocontrol unit.

Although the work started in the summer of 1974, the dye laser was not received until April 1976. By that time the electric apparatus, the oven, and the system of magnetic screens were ready. By the end of 1976 we succeeded in substantially modifying the laser and converting it to the single-frequency tunable operating regime. The absorption spectrum of the bismuth vapor was then obtained in a region of several angstroms, where the hyperfine-structure lines of the 648-nm transition should be observed. The ${}^4S_{3/2} - {}^2D_{5/2}$ transition used to measure the parity nonconservation can be of

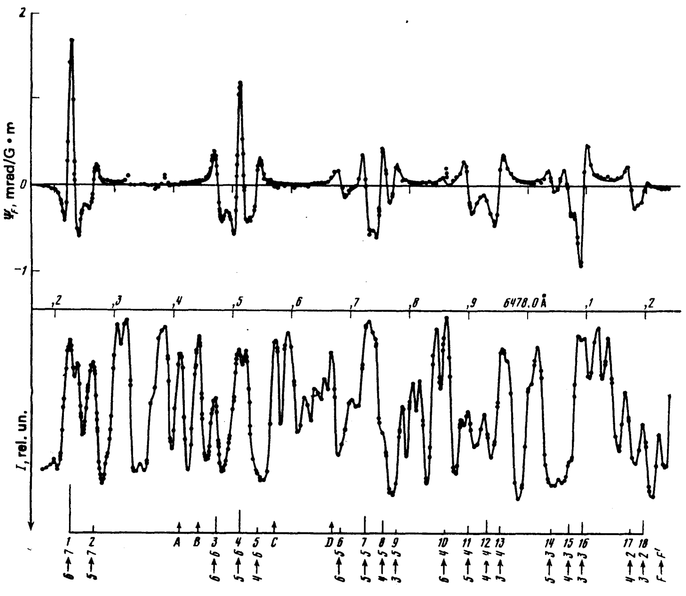

FIG. 6. Faraday rotation and absorption spectrum of bismuth vapor in the region of the $\lambda = 648$ nm transition.

either the magnetic dipole or the electric quadrupole type. Since the spin of the bismuth nucleus is 9/2, the hyperfine structure of this transition consists of 12 lines with ΔF equal to zero and ±1, and 6 lines with ΔF equal to ±2. The lines with ΔF equal to zero and ±1 correspond to magnetic-dipole transitions with admixture of quadrupole transitions. It is these that were used to measure the parity nonconservation effect. The transitions with $\Delta F = \pm 2$ are pure quadrupole, so that the parity nonconservation effects are weaker here by approximately $\alpha^2 \approx 10^{-4}$ times. These effects are strongly suppressed also on the molecular lines of bismuth, whose partial vapor pressure at temperatures ≈1200 °C is approximately equal to the pressure of atomic bismuth.

Figure 6 shows the bismuth-vapor absorption curve measured in the region of the transition ${}^4S_{3/2} - {}^2D_{5/2}$. As seen from the figure, the hyperfine structure is covered by the strong absorption spectrum of molecular bismuth, so that the known distances between the hyperfine components, which were first measured back in 1946 by Mrozowski,[19] cannot yield the positions of the atomic lines. They were identified by measuring the Faraday effect in that region of the spectrum. In the study of the dependence of the Faraday rotation on the wavelength, we used the standard scheme, the advantage of which is that, unlike the frequency-modulation technique, the measurements need be made only at the maxima and minima of the transmitted-light intensity. Since we are now dealing with measurement of angles $\sim 10^{-4}$ rad, it is possible to neglect in this case the serious shortcoming of the standard scheme, namely the presence of additional matter, at any rate the Faraday cell, between the polarizer and analyzer, which can lead to various false effects. To change the measurement scheme, the installation was revamped. A Faraday cell was placed between the polarizer and the cell with the vapor and modulated the reference angle at a frequency 1 kHz. The laser wavelength was scanned in this case at a frequency 0.01 Hz.

Figure 6 shows the results of the measurement of the Faraday rotation on the ${}^4S_{3/2} - {}^2D_{5/2}$ atomic transition. It shows also a plot of the effect, calculated by Sushkov and Flambaum on the basis of Refs. 14 and 20. In the calculation we assumed for the reduced amplitude of the *M*1 transition the value $0.55e/2m$ obtained in Ref. 14; the error of this value does not exceed 2%. From a comparison of the measured and calculated Faraday angles we determined the partial vapor pressure of the atomic bismuth, which agreed with the value listed in the handbook[21] within the limits of the measurement accuracy, 5–10%.

A comparison of the theoretical and experimental results yielded the following values of the free parameter of the calculation: the impact broadening of the lines does not exceed several percent of the Doppler broadening; the radial integral of the $E2$-transition amplitude $\langle r^2 \rangle = (9.0 \pm 0.6)a^2$; the dipole and quadrupole hyperfine splitting constants of the ${}^2D_{5/2}$ level are equal to $A = (2503.8 \pm 1.6)$ MHz and $B = (2 \pm 23)$ MHz. The indicated value of $\langle r^2 \rangle$ agrees with the results obtained at Oxford.[22] A somewhat higher accuracy in the determination of the constants A and B was recently attained by Dembczynski *et al.*[23]: $A = (2502.86 \pm 0.56)$ MHz and $B = (23 \pm 11)$ MHz. The calculated value of the constant is given in Ref. 24; $B = (6 \pm 5)$ MHz.

These data were obtained from an analysis of the Faraday effect. They were used for a quantitative interpretation of the results of the measurements of parity nonconservation in the last measurement run, with an automatized system for the gathering and reduction of the data.

The first Faraday-rotation curves were obtained with a less sophisticated installation. But even they made it possible to establish reliably and unambiguously the positions of the hyperfine-structure lines of atomic bismuth relative to the absorption spectrum, and to proceed directly to the study of parity nonconservation. The measurements were first made on the molecular control lines. At that time the entrance and exit windows of the cell were made of glass, while the analyzer and polarizer were Frank-Ritter prisms in which one of the components of the polarization of the light was quenched, beam-splitting plates and mirrors were used to obtain a reference light beam incident on the photomultiplier PM-1, and a Faraday cell was used to change the angle $+\theta$ to $-\theta$. There were no light diffusers in front of the photomultipliers. The first measurements on the control molecular lines yielded signals that imitated parity nonconservation on a level approximately 10^3–10^4 times higher than expected for the working lines. Microscopic displacements of any element of the apparatus reversed the signs of the signals. The causes of the observed phenomena became clear after some time. When the wavelength is scanned, a synchronous spatial restructuring of the laser beam takes place. When the modulated light is incident on the photomultipliers, the inhomogeneity of the photocathodes generates the first harmonic. To suppress this effect, cavities coated inside with white diffusely scattered paint were placed in front of each photomultiplier. The cavities had an opening for the entry of the laser beam and an opening for the exit of the diffusely scattered light towards the photocathode. The cavities ensured good mixing of the light, so that even at considerable displacements of the photomultiplier with the diffuser relative to the laser beam no change was observed in the first-harmonic signal. The use of diffusers reduced by three or four orders of magnitude the first-harmonic signal, but the control data still revealed effects at levels expected for the working lines. All the remaining false effects were attributed to the same synchronous restructuring of the beam. The point is that all optical elements produce ellipticity that is not homogeneous over the area, and as a result a first-harmonic signal is produced in the course of the synchronous restructuring. This signal varies furthermore with time when the beam deviates smoothly or when its structure changes. Much unpleasantness was caused by all the plane-parallel glasses placed along the beam axis. Thus, for example, an attempt was made to use an interference light filter to suppress the light from the oven. This was accompanied by observation of a smooth change of the first-harmonic signal, with an approximate period of one hour. It turned out to be due to a shift of the light filter, which was secured with modeling clay. Particularly dangerous was light reflected into the laser; even attenuation of the light by up to a factor 10^5 did not eliminate the uncontrollable feedbacks in the system. In the main, all the subsequent work was aimed at simplifying the optical system. As a result, nothing but bismuth and helium was left between the polarizer and the analyzer.

The preparation of the apparatus for a measurement run started with work on a molecular line having a large width. This made it possible to increase the scanning amplitude by 4–5 times compared with normal operation. By the same token, the effects connected with the synchronous tuning of the laser beam increased. The intensity of the laser light also increased in comparison with the working intensity by approximately one order of magnitude (in this case the lasing was on several longitudinal modes). All this made it possible to shorten the required observation time. Under these conditions, the false effects were minimized by shifting the polarization prisms. After this, no changes were made in the positions of the prisms, lenses, diaphragms, etc. during the measurement run. In the course of the run, measurements were made alternately on the working and control lines. At the end of each measurement, a magnetic field of $\approx 10^{-2}$ G was turned on. The angle of rotation of the plane of polarization by application of the magnetic field, measured by the same frequency-modulation method, served as a control on the operation of the setup and was used to normalize the parity nonconservation effect. These alternating measurements on working and control lines constituted one run. During the preparation for the first three measurement runs, the level of the first harmonic in the difference signal was not always stable in time. As a result, the preparation for the run sometimes lasted about a month.

Altogether, three sets of measurements were made. The first set consisted of one run, while the second and third consisted of two runs each. Between the sets, the apparatus was modified many times. Two purposes were pursued: the first was to attain stable operation or, at least to increase the time of the quiescent behavior of the system; the second was an attempt to eliminate all possible systematic errors. For example, during the first set of measurements the polarizer was rotated through an angle $\pm\theta$ and was so constructed that the position of the light beam on the photomultiplier remained unchanged in the course of the rotation. In the second set the analyzer was rotated and the photomultipliers were immobile. In the third set of measurements the photomultipliers were rotated together with the analyzer in such a way that the relative positions of the light beams and of the photomultipliers remained unchanged. The axis of rotation of the photomultipliers and of the analyzer prism coincided with the axis of the laser beam inside the cell, therefore the rotation of the analyzer prism did not lead to a displacement of the light beam over the prism. As already mentioned, the third measurement run was automatized. In the course of the study, the system of diaphragms, their dimensions, and their relative placements were substantially altered. As a result of the successive improvement of the system, no instability in the first-harmonic signal was observed in the last measurements.

In the first set, the measurements were made on seven lines.[25] On four of them, (lines 1, 3, 7, and 12 of Fig. 6) one could expect a rotation of the plane of polarization of the lines. Three lines (two molecular and one quadrupole, A, C, and 10 on Fig. 6) served to monitor the operation of the apparatus. In this set of measurements the polarizer was rotated through an angle $\pm 1 \times 10^{-3}$ rad. The sign of the angle was reversed every 200 sec, and to eliminate transient processes the results obtained during the first 50 seconds after the reversal of the polarizer were excluded from the data reduction. The integration time of the synchronous detectors in this run was 15 sec. Ten measurements were made on each line for each position of the polarizer. The total time of measurement on a line, including the time with the magnetic field on, was approximately 1.5 hour. The signals proportional to the measured effects and to the intensities of the incident and reflected light, as well as the feedback signals, were recorded with a five-channel automatic plotter.

In the first measurement set the average rotation angle on the lines corresponding to the $M1$ transitions with $\Delta F = 0, \pm 1$ amounted to $(-6.7 \pm 1.6) \times 10^{-8}$ rad, whereas the average rotation angle on the control lines was $(2.1 \pm 1.5) \times 10^{-8}$ rad. The result differs from zero by more than four standard deviations, thus unequivocally pointing to parity nonconservation in atoms.

In this set of measurements there was no sectionalized winding within the magnetic screen, so that it was impossible to determine, from the Faraday rotation, the length of the region occupied by the bismuth vapor. It was roughly estimated from the location of the points at which the bismuth vapor condensed. Nor was it possible to obtain a sufficiently good normalization of the measured effect against the magnetic measurements. The point is that the Faraday rotation is very sensitive to the position of the generation modes of the laser relative to the lines of atomic bismuth, and this position was not known with sufficient accuracy in this set of measurements. Taking these circumstances into account, an additional factor K was introduced in the comparison of the results with the predictions based on the Weinberg-Salam model. This factor took into account the uncertainty in the normalization of the effect and was estimated at from 0.5 to 1.5. The mean value of the measured angles relative to those calculated on the basis of the work of Novikov *et al.*[13] was, in accordance with the results of this set of measurements

$$\langle \Psi_{exp}/\Psi_{theor} \rangle = (1.4 \pm 0.3) \cdot K. \tag{5}$$

In the second set[26] the measurements were performed on the working lines 1, 3, 7, 12, and 18, and the control measurements were made on the lines 2, A, B, D, and 17 (see Fig. 6). In this set of measurements the analyzer was rotated through an angle $\pm 2.5 \times 10^{-3}$ rad, somewhat larger than the rotation of the polarizer in the first set. A sectionalized winding was placed inside the magnetic screen and used to determine, by measuring the magnetic rotation, the distribution of the vapor density of the atomic bismuth along the cell axis. The measurement procedure in this set was the same as in the first, but the contour of the line of light absorption by the bismuth vapor was determined more carefully.

From a comparison of the magnetic-rotation angles measured on the same lines in the first and second sets, we calculated the coefficients for the conversion of the results from one set to the other. It should be noted that in the second set we used larger light-wavelength scanning amplitudes than in the first, so that the magnitude of the expected effect was changed. The data of the first set, referred to the condition of the measurements of the second set, supplemented the results of the latter and were jointly reduced. As a result, the average angle of rotation was $(-3.1 \pm 0.5) \times 10^{-8}$ rad on the working lines and $(1.0 \pm 0.5) \times 10^{-8}$ rad on the control lines. Because of the contribution of the wings of the $M1$ transitions, a small effect should be observed also on the control lines, and furthermore of opposite sign, inasmuch as the signs in the region of the anomalous and normal dispersions are opposite. The average expected rotation angle for the control lines is approximately 0.2×10^{-8} rad. The average of Ψ_{exp}/Ψ_{theor} obtained in these measurements, turned out to be

$$\langle \Psi_{exp}/\Psi_{theor} \rangle = 1.04 \pm 0.28. \tag{6}$$

This figure differs by 6% from that given in Ref. 26, because in the latter Ψ_{theor} was calculated using a more accurate[14] value $(0.55e/2m)$ for the reduced amplitude of the $M1$ transition. The relative error in (6) is somewhat larger than in the value of the average rotation angle for the working lines, inasmuch as the discussed result is subject not only to statistical errors but also to errors connected with the still remaining uncertainty in the position of the laser modes relative to the bismuth atomic lines.

Prior to the third set of measurements, the apparatus was substantially revamped. An automatic system for controlling the experiment and for gathering the information was introduced. The photomultipliers were rotated together with the analyzer. An electromechanical system was introduced to reverse the analyzer angle, whose value was increased to 4×10^{-3} rad. The integration time in this set was decreased to 1 second and the ADC was used every 0.1 sec to measure and record into the memory of the computer the signals from the output of the synchronous detector and the integrated signals of the intensities of the incident and transmitted light. The special fast ADC block recorded, in synchronism with the light wavelength scanning frequency, the instantaneous values of the intensity of the transmitted light at 256 points with 5 μsec spacing. These measurements were repeated 400 times at intervals of 0.1 sec, after which the sign of the angle θ was automatically reversed. To eliminate transient effects, the first 100 measurements after the reversal of the angle were not used in the reduction. A total of 20 pairs of analyzer-angle reversals were carried out in each measurement on a line, after which measurements were performed with a magnetic field $\pm 10^{-2}$ G turned on. These measurements, alternately on the working and control lines, were made 26 times each on the lines 1, 2, and A and 13 times on the line 3. At the end of the work on each line, the results of the measurements of the signals and of the absorption line shape, which were accumulated in the computer, were printed out. The data obtained in this manner were reduced jointly with the results of the measurements of the shape of the Faraday curve and of the absorption spectrum, which were investigated in detail in the region of the first two groups of lines of the hyperfine structure of the ${}^4S_{3/2} - {}^2D_{5/2}$ transition. As a result we determined with sufficient accuracy the positions of the laser modes relative to the atomic lines and the intensity of the transmitted light at fixed wavelengths. From the theoretical plots of the expected effect and of the Faraday rotation, each laser mode was set in correspondence with the values of the expected angles. These values were used further to reduce the results and to obtain Ψ_{exp}/Ψ_{theor}.

The results of the measurements of this set[27] are given in Table II. As seen from the table, measurements on the control lines point to the absence of systematic errors, in particular, errors connected with the residual magnetic field. From the measurements on the working lines we obtained

$$\langle \Psi_{exp}/\Psi_{theor} \rangle = 1.09 \pm 0.17.$$

In this case the presented error is purely statistical.

TABLE II. Results of third set of measurements (in units of 10^{-8} rad).

Line	$F - F'$	First run	Second run	Ψ_{theor} ($\sin^2\theta = 0.25$)
1	6–7	−12.8±2.8	−13.0±3.3	−11.6
2	5–7	0.3±3.3	−0.9±1.4	+0.3
3	6–6	−3.7±2.8	−2.3±2.4	−3.2
A	–	−2.6±2.6	0.6±1.7	+0.1

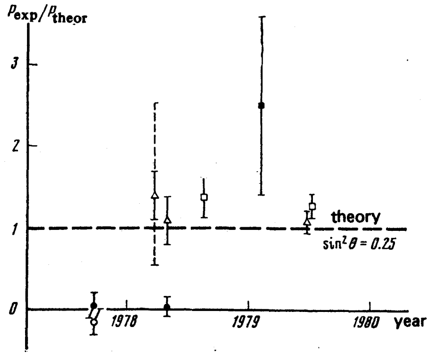

FIG. 7. Chronological sequence of the results of the measurements of the parity nonconserving interaction of the electrons with the nucleons (P_{exp}—parameter characterizing parity nonconservation, P_{theor}—expected value within the framework of the Weinberg-Salam model at $\sin^2\theta = 0.25$): ●—Seattle,[28,29] ○—Oxford,[30] △—Novosibirsk,[25-27] □—Stanford,[31] ■—Berkeley.[32]

The fact that in the first two measurement sets we took into account the uncertainty in the positions of the lines does not mean at all that there were uncontrollable errors in those cases. The results of the measurements on the control lines point to the absence of systematic errors in all measurement sets.

As seen from the presented data, the results obtained in all sets agree well with one another. It must be emphasized once more that in all the sets the measurements were carried out under different conditions, in particular, the prisms of the analyzer and polarizer varied from set to set. All this allows us to regard the results of the three measurement series as independent.

Averaging the results of the three measurement series, we have

$$\langle \Psi_{exp}/\Psi_{theor} \rangle = 1.07 \pm 0.14$$

or, using a symbol most frequently encountered in the literature, namely R, which stands for half the degree of circular polarization with the sign reversed ($R = -P/2$), we obtain

$$R = (-20.2 \pm 2.7) \cdot 10^{-8}.$$

Thus, the results obtained at our institute prove the existence of parity nonconservation in atomic transitions and confirm quantitatively the Weinberg-Salam model.

Figure 7 shows, in chronological sequence, the results of the measurements of the parity nonconservation in the interaction of electrons with nucleons, obtained in different laboratories. The ordinate is a parameter characterizing the ratio of the degree of parity violation to the predictions of the Weinberg-Salam model at $\sin^2\theta_{WS} = 0.25$.

The results of the Seattle and Oxford groups shown in Fig. 7 point to the absence of parity nonconservation in atoms and contradict the predictions of the Weinberg-Salam model. However, the lastest results $P_{exp}/P_{theor} = 0.7 \pm 0.07$ of the Seattle group,[33] obtained with a semiconductor laser on the infrared line $\lambda = 876$ nm, clearly point to the existence of the effect. These results are not shown, however, in Fig. 7 inasmuch, as indicated by their authors, these measurements still contain systematic errors noticeably exceeding the presented statistical error. For the same reason we do not show the last results of the Oxford group,[34] in which the effect is definitely observed at the level of the predictions of the Weinberg-Salam model. Both groups are presently studying and elminating the instrumental errors.

The first results of measurements of the parity nonconservation effects were recently reported by a group from the Lebedev Institute (Moscow).[35] Their result is $P_{exp}/P_{theor} = -0.02 \pm 0.1$. This group uses the same measurement procedure as the Oxford group. Their results also exhibit instrumental errors greatly exceeding the presented statistical error. It must be noted, however, that the results of these two groups differ significantly. Only further improvement of the measurement procedure during the last few years has enabled the Seattle and Oxford group to register the parity-nonconservation effect at the level expected within the framework of the Weinberg-Salam model. As to the results obtained in Moscow, they are based on a single measurement lasting several hours (three hours with bismuth vapor and 2.5 hours at lower pressure). In the latter experiment no control measurements were made analogous to those that enabled the Seattle and Oxford group to observe the systematic errors of the employed procedure.

The groups mentioned above have used a procedure in which the Faraday cell modulates the reference angle θ and the rotation of the plane of polarization is revealed by the change of the signal of the first harmonic when the laser wavelength is retuned in the region of the $M1$ transition of atomic bismuth. These groups work with practically no magnetic screen and distinguish between the Faraday rotation and the rotation due to parity conservation by their different dependences on the wavelength. Thus, the Oxford and Moscow groups measured the parity conservation on the leading line of the $M1$ transition $\lambda = 648$ nm as the difference of the signals obtained at two values of the wavelength, at which the Faraday rotation is equal to zero, and the parity nonconservation effect reaches its extremal values. We note that when the laser wavelength was varied, even without bismuth vapor, all three groups revealed a change in the signal of the first harmonic, corresponding to a rotation angle ~10^{-7} rad. The appearance of such large false signals, which are furthermore unstable in time, makes it difficult to obtain reliable quantitative results by the standard procedure of measuring small angles of the rotation of the polarization plane of the light.

In measurements with bismuth vapor, there is a danger of penetration of the alternating magnetic field from the Faraday cell into the poorly screened cell with the bismuth vapor, resulting in light ellipticity that varies with the frequency of modulation of the reference angle θ. Even a Faraday-cell field weaker by a factor 10^5 can produce false signals that can cancel out those expected in accord with the Weinberg-Salam model. In fact, the signal from the photodetector is proportional to the intensity of the light passing through the analyzer, and depends both on the angle θ between the light polarization plane and the analyzer axis, and on its ellipticity ε:

$$V \propto I(\theta^2+\varepsilon^2),$$

where I is the intensity of the light passing through the bismuth vapor,

$$\theta=\theta_0 \sin \Omega t+\Psi_{PNC}, \quad \varepsilon=\varepsilon_0+\varepsilon_H \sin \Omega t,$$

θ_0 and Ω are the amplitude and frequency of the modulation of the angle of rotation of the polarization plane in the Faraday cell, ε_0 is the light ellipticity due to imperfection of the optical elements, and ε_H is the ellipticity due to the dichroism of the bismuth vapor in the alternating magnetic field from the Faraday cell.

Thus, the amplitude of the first-harmonic signal is proportional to

$$V_1 \propto I[\theta_0\Psi_{PNC}+\varepsilon_0\varepsilon_H].$$

We call attention to the fact that Ψ_{PNC} and ε_H frequently exhibit a dependence on λ in the absorption-line region. The usual values in the experiments are $\theta_0 \sim 10^{-3}$ rad and $\varepsilon_0 \sim 3\times 10^{-4}$. Consequently an alternating magnetic field $\sim 10^{-3}$ G in a cell with bismuth vapor can mask the parity nonconservation effect (we note that in Faraday cells one usually employs fields stronger than 10^2 G).

We present one more example of an effect that can imitate parity nonconservation. In experiments in which the heater of the cell with the bismuth vapor is not turned off during the measurement time, a slight modulation of the laser wavelength at the heater frequency leads to a signal

$$V \propto I\theta^2 \propto \left(\theta_0 \sin \Omega t+\Psi_{PNC}+\Psi_F \sin \omega t+\frac{\partial \Psi_F}{\partial \lambda}\Delta\lambda \sin^2 \omega t\right)^2,$$

where ω is the frequency and $\Delta\lambda$ is the modulation amplitude. In this case the amplitude of the first-harmonic signal is

$$V_1 \propto \theta_0\left(\Psi_{PNC}+\frac{1}{2}\frac{\partial \Psi_F}{\partial \lambda}\Delta\lambda\right).$$

We note that here, too, Ψ_{PNC} frequency has the same dependence on λ as $\partial\Psi_F/\partial\lambda$. In real conditions it suffices to have $\Delta\lambda \sim 10^{-3}$ of the Doppler line width to imitate the effect.

Since the procedure used by us has demonstrated the absence of systematic false effects at a level $\sim 10^{-8}$ rad, there is every reason for hoping that with more powerful lasers it will permit measurement of angles 10^{-9}–10^{-10} rad, so that it will become possible to obtain new information on the structure of the weak interaction and, in particular, to investigate in atoms parity-nonconservation effects that depend on the nuclear spin.

The authors are deeply grateful to I. B. Khriplovich who suggested the undertaking of this work, to A. I. Vaĭnshteĭn, V. N. Novikov, O. P. Sushkov, and V. V. Flambaum, discussions with whom were extremely useful, to A. N. Skrinskiĭ, V. A. Sidorov, and I. I. Gurevich for constant interest in the work, to L. V. Ankudinov, A. M. Batrakov, V. R. Kozak, E. A. Kuper, I. F. Legostaev, P. A. Litvinov, V. S. Mel'nikov, V. I. Sverdlov, V. I. Fominykh, V. M. Khorev, V. P. Cherepanov, and A. I. Shekhtman for help in the construction and preparation of the apparatus and in the performance of the experiment.

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Translated by J. G. Adashko