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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 ($6p^3 J=\frac{3}{2}\rightarrow 6p^3 J=\frac{5}{2}$).[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.

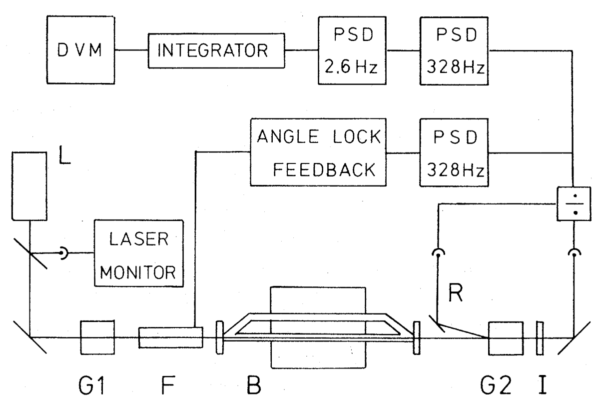

FIG. 1. Schematic diagram of appartus. L, dye laser; $G1$, $G2$ crossed Glan-Thompson polarisers; F, Faraday modulator; B, bismuth oven; I, interference filter; R, intensity reference. The slow "angle lock feedback" controls a dc field applied to F (see text).

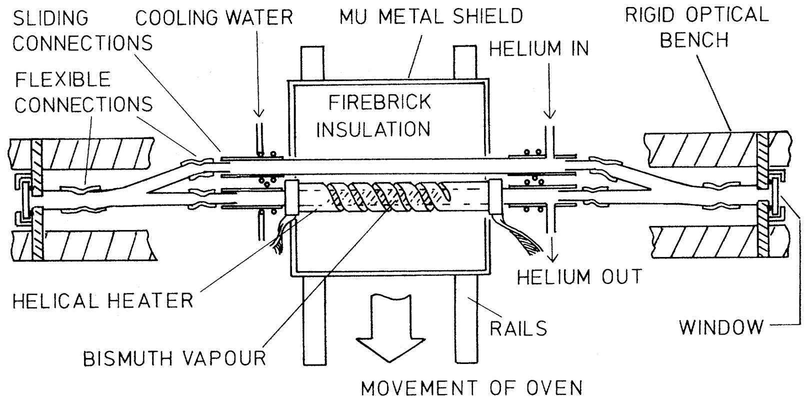

FIG. 2. Construction of bismuth oven. The oven is coupled to the optical bench only through flexible or sliding connections. Transverse movements of the oven, allowing the laser light to pass through either the dummy or the bismuth-filled tube, cause no movement or strain in the windows or other optical components.

The oven itself consists of a ceramic tube 2 cm in diameter and 1 m long. The central region of about 50 cm is at 1500 K. Transverse movement of the whole oven assembly permits the laser light to pass through either the oven or a dummy tube without moving any optical components; the strain-free silica windows are in mounts rigidly fixed to an optical bench standing independently of the oven assembly. The helium buffer gas is at a pressure of about 160 Torr. The Faraday modulator (a water cell in a solenoid) gives an additional controlled rotation φ_M of up to a few milliradians to the plane of polarization. Light transmitted through the system is detected on a *p-i-n* diode; a second detector monitors the transmission of the oven to provide normalization.

The description of the experimental procedure can be subdivided as follows:

Measurement of small angles.—The intensity transmitted through nearly crossed polarizers is given by

$$I = I_0(\varphi_M + \varphi_R + \varphi_{PNC})^2 + BI_0, \qquad (1)$$

where φ_{PNC} is the bismuth optical rotation of interest, and φ_R is the sum of any residual angles due to slight misalignment of the polarizers, optical rotation in the windows, etc. B is the residual, angle-independent transmission through the polarizers, typically $\simeq 10^{-6}$.

In order to obtain a signal linear in φ_{PNC} we modulate φ_M sinusoidally at a frequency $\omega/2\pi = 328$ Hz and use phase-sensitive detection (Fig. 1) to isolate that part of the signal which varies at frequency ω. This is given by

$$I(\omega) = 2I_0\varphi_M(\omega)(\varphi_R + \varphi_{PNC}).$$

$I(\omega)$ is thus proportional to the sum of any additional angles of rotation in the system. We have determined the angle sensitivity of our apparatus by adding to φ_M a small known constant angle $\varphi_M^{(dc)}$; with a time constant of 2 minutes our sensitivity at the one standard deviation level was 1×10^{-8} radians. This is not far short of the limit set by photon shot noise.

Wavelength discrimination.—To discriminate against φ_R, we make use of the very sharp frequency dependence of φ_{PNC} close to the resonance. A change in laser wavelength of approximately one part in 10^6 across the center of the spectral line will give a change in optical rotation $\Delta\varphi_{PNC} = R$, whereas the corresponding fractional change in φ_R will be small, since this angle is expected to show no marked features at the bismuth resonance. The frequency change required to give this maximum change in φ_{PNC} also enables us to discriminate against possible bismuth Faraday rotation, as described below.

To exploit this frequency dependence of φ_{PNC}, we cause the laser wavelength to switch from side to side of the spectral line with a repetition rate of 2.6 Hz. The corresponding change in $I(\omega)$,

$$\Delta I(\omega) = 2I_0\varphi_M(\omega)(\Delta\varphi_{PNC} + \Delta\varphi_R), \qquad (2)$$

is isolated by electronic switching, the output being integrated. It follows from (2) that $\Delta\varphi_R$, the wavelength-dependent part of the residual angle, rather than φ_R itself contributes to the signal. For convenience, the mean value of φ_R is set to zero by applying an additional magnetic field to the Faraday cell. The field is set by a feedback system (shown in Fig. 1) with a time constant long compared with the period of the laser wave-

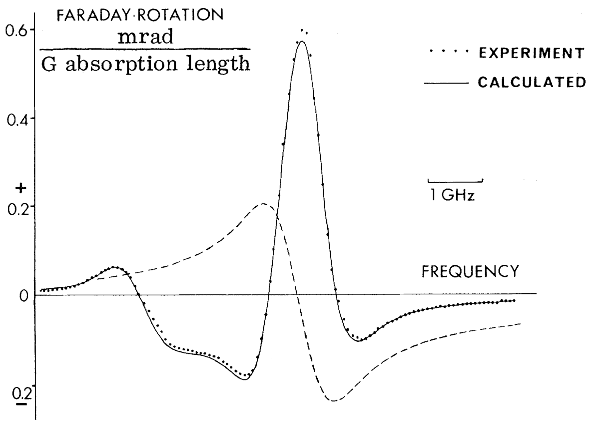

FIG. 3. Rotations near the $F=6-7$ component in the 648-nm line of atomic bismuth. The E_2 feature ($F=5-7$) can be seen on the low-frequency wing of the Faraday curve. The dashed line shows the predicted form of PNC optical rotation on an arbitrary scale.

length switching.[11]

$\Delta\varphi_R$ turns out not to be negligible. With the bismuth vapor absent, so that $\Delta\varphi_{PNC}=0$, we find an angle $\Delta\varphi_R$ which is of order 2×10^{-7} rad. Unfortunately, it varies with time over a period of minutes and depends sensitively on the setting of the laser and on the optical path through the polarizers. While we believe we understand this effect in terms of imperfections in the polarizers combined with changes in laser beam intensity distribution, we have not so far been able to reduce it significantly.

Bismuth dependence.—Separation of $\Delta\varphi_{PNC}$ from $\Delta\varphi_R$ is achieved by a series of "sandwich" intercomparisons using the double oven. Each sandwich consists of four, 4-min measurements of $\Delta I(\omega)$, two with the bismuth oven in position and two with the dummy tube. The relative order is A,B,B,A with the assignment of A and B to oven and dummy on a random basis.

Faraday calibration.—Detailed measurements of the Faraday effect for the whole $J=\frac{3}{2}-J=\frac{5}{2}$ hyperfine multiplet have been made; the rotation in the vicinity of the 6–7 hyperfine component is reproduced in Fig. 3. The feature on the low-frequency wing, satisfactorily reproduced in the theoretical fit, corresponds to the pure E_2 transition 5–7.

The Faraday effect is also used to normalize the optical rotation measurements in a very direct way. The application of a known dc current to the heater coil enables us to measure the dc Faraday effect φ_F using exactly the same system as in the optical rotation measurements. This method is independent of both optical depth and apparatus calibration.

Our ability to determine the bismuth Faraday rotation accurately enables us to avoid apparent PNC rotation arising from the Faraday effect in any small residual magnetic field. We set the laser wavelengths so that the change is between points of both equal and almost zero Faraday rotation, which closely corresponds to the maximum difference in φ_{PNC}.

Over a period of months we have made some 120 sandwich intercomparisons; the results are set out in Table I. We have also included for completeness an earlier series[4] carried out with a single oven in which $\Delta\varphi_{PNC}$ and $\Delta\varphi_R$ were separated by varying the bismuth density through changes in oven temperature. The quoted limits on the present data are purely statistical though in the case of the single-oven data allowance has been made for a possible systematic error arising from the problem of comparing measurements made with varying oven temperatures.

We conclude by noting that our null result is in disagreement with the theoretical prediction. A similar result is found in the accompanying paper[12] which describes a related experiment on the 876-nm $J=\frac{3}{2}-J=\frac{3}{2}$ transition in atomic bismuth.

TABLE I. Summary of results for $R=\mathrm{Im}\,(E_1/M_1)$ in 648 nm of atomic bismuth.

Experiment	Number of measurements	10^8R
Single oven	73	$+10\ \pm12$
Double oven	48	$+2.2\ \pm7.0$
Improved	73	
double oven	73	$+0.6\ \pm7.0$
	Combined result	$+2.75\pm4.7$
Theory		-30

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[10]In fact the transition has an E_2 contribution (see Fig. 3). This produces no rotation, but has been taken into account in our calibration, etc.

[11]The details of this and other feedback loops, gating circuitry, etc., will be described elsewhere.

[12]L. L. Lewis *et al.*, preceding Letter [Phys. Rev. Lett. 39, 795 (1977)].

Time-Delayed Li, Be, and B Autoionization Spectra Excited in Low-Energy (200 keV) Single Gas Collisions

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Metastable, autoionizing high-spin states are studied using the ion-beam time-of-flight method in connection with single-collision excitation. High-resolution, time-delayed spectra are obtained from Li, Be, and B excited in 200-keV impact on CH_4. Evidence is found for the $(1s2s2p^2)^5P$ state in B II. Excitation energies for the observed quartet and quintet states are given, and the branching ratio associated with the B II $(1s2s2p^2)^5P$ decay is estimated.

Electron spectroscopy is now established as a powerful technique for the study of ion-atom collision processes.[1,2] However, until now, no time-delayed, electron-emission studies using single gas excitation have been performed. Therefore, excitation mechanisms of metastable, autoionizing high-spin states from fast-moving projectiles have not been investigated in the context of ion-atom collisions. In this Letter, we present for the first time high-resolution, time-delayed Li, Be, and B electron spectra measured under single-collision conditions with ground-state ion beams. It is demonstrated that specific metastable states are strongly populated, and the corresponding autoionizing transitions can be isolated. Therefore, the excitation cross sections and angular dependences of such autoionization lines can be measured. In particular, the nonisotropic population of magnetic substates[3-5] of lithiumlike ^4L and berylliumlike ^5L terms can be studied. We further note that (i) excitation by means of single gas collisions provides high-energy resolution, and (ii) variation of the collisional parameters (e.g., projectile, target, impact energy, observation angle, delay time) makes possible a selective study of specific states such as $(1s2s2p)^4P^\circ$ and $(1s2s2p^2)^5P$. This facilitates a complete line identification of the observed autoionization features. The high resolution provided by this technique permitted analysis of excitation energies, branching ratios, and spectroscopic character of several unusual lines; our results are presented below. Lifetimes and metastable fractions with respect to the single-collision process are topics of the planned extension of this work.

Generally, metastable autoionizing states are accessible for few electron systems from projectiles using foil excitation.[6-13] These beam-foil measurements were primarily limited to studies of electrons ejected at 42.3° to the direction of the incident ion beam. The Oak Ridge group reported delayed electron spectra, using high beam energies and highly stripped heavy ions.[6-8,12] Similar work at low beam energies and for light projectiles (Li, Be, B, and C) were investigated by Bruch and co-workers.[9-11,13] Because of kinematical broadening effects arising from the foil-excitation process, only limited resolution was obtained, especially at low beam energies. Previous direct observations of metastable autoionizing states, produced by single-ion-atom collisions, were performed by Ziem, Bruch, and Stolterfoht[14] and by Stolterfoht *et al.*[15] Ziem, Bruch, and Stolterfoht bombarded Li atoms in the vapor phase with 200-keV He^+ ions, and Stolterfoht and co-workers directed 200-MeV Xe^{31+} onto Ne. In both cases, lithiumlike $(1s2s2p)^4P^\circ$ target states are very likely to be created; however, because the excitation was of the target atom, no time-delayed anisotropic Auger electron emission could be studied.

Using single gas excitation and small observation angles, we have recently shown that high-