Nuclear Magnetic Moments of ^{205,207,209}Bi Isotopes—Hyperfine Structure of the 15-day ^{205}Bi 3067-Å Line*

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The hyperfine structure of the 3067-Å line of 15-d ^{205}Bi was measured by optical spectroscopy. The results are $A(^4P_{1/2}) = 166(4)\times10^{-3}$ cm^{-1}, giving $\mu = 4.13(11)\mu_N$, and 192(14) $\times10^{-3}$ cm^{-1} for the ^{205}Bi-^{209}Bi isotope shift. A reexamination of the ^{207}Bi hfs shows accord with previous spectroscopic results [$\mu = 4.07(2)\mu_N$], but not with the recent nuclear orientation finding by Johnston, Kaplan, and Stone that $\mu(^{207}$Bi) is substantially larger than $\mu(^{209}$Bi). Calculations of magnetic moments of odd bismuth isotopes, including configuration mixing and pion-exchange contributions, are in agreement with our experiments.

In a recent Letter Johnston, Kaplan, and Stone, reported[1] a measurement of the nuclear magnetic moment of 30-yr ^{207}Bi by nuclear orientation in the hyperfine field of a nickel host. Their result, $\mu(^{207}\text{Bi}) = 4.63(25)\mu_N$, is appreciably larger than the magnetic moment[2] $\mu(^{209}\text{Bi}) = 4.080(2)\mu_N$. It also differs substantially from the value of $\mu(^{207}\text{Bi}) = 4.07(2)\mu_N$ that would be obtained from our optical spectroscopic hfs measurement[3] with the assumptions[4] that $I = \frac{9}{2}$ and that the effects of distributed nuclear magnetization[5,6] (Bohr-Weisskopf effect or hfs anomaly) are negligible.

The result of Johnston, Kaplan, and Stone was furthermore presented in comparison to the trend of magnetic moments of other odd-A bismuth isotopes, including that of ^{205}Bi. The latter value, $\mu(^{205}\text{Bi}) = 5.5\mu_N$, was, however, obtained from a rough estimate[7] which the results reported here do not support.

Because the magnetic moments of nuclei in the vicinity of doubly magic numbers, and in particular those of bismuth, play an important part in nuclear-structure theory[8] and in the observation of the effects of meson exchange[9] on the nucleon g values, reliable, directly determined experimental values are essential. In view of this, we have measured by optical spectroscopy the hfs of 15-d ^{205}Bi and examined further optical data for 30-yr ^{207}Bi. Specifically, the latter was done in response to the suggestion by Johnston, Kaplan, and Stone that the discrepancy between their new result and the value obtained from our earlier optical spectroscopic measurement of the hfs of ^{207}Bi was due to a likely contamination by natural bismuth in the latter.

^{205}Bi.—We have measured the hfs of the $6p^27s\ ^4P_{1/2}$-$6p^3\ ^4S_{3/2}$ 3067-Å resonance line with the use of our 10-m focal-length Czerny-Turner monochromator, in which a 25-cm-wide diffraction grating is used near autocollimation at the blaze angle $\approx 63°$. An estimated 10^{15} bismuth atoms were produced with the Princeton University cyclotron in the reaction ^{207}Pb(p, $3n$)^{205}Bi at 30 MeV. The target was natural lead. The bismuth was chemically separated from the lead target using a solvent extraction method. After this, the sample was isotopically separated at Argonne National Laboratory. Approximately 10^{13} bismuth atoms were then available to make our electrodeless lamps, in a manner similar to that described in Ref. 3. Although the mass spectra could serve as an indicator of isotopic purity, because further processing of the target material might introduce natural isotope contamination, the only reliable test, including ^{209}Bi contamination, both in this case and for ^{207}Bi, is the spectrogram itself. This is manifested by the observation of distinct spectra for each isotope. The isotope identification relies on γ-ray spectra and half-life determination. The number of ^{205}Bi atoms transferred into the lamps, as estimated from the radioactivity, was in agreement with the typical optical-spectrum intensities observed in these experiments. This was also the case for the ^{207}Bi lamps.

The measured[7] spin of ^{205}Bi is $\frac{9}{2}$. The hfs pattern consists of six components as shown in Fig. 1. All of these components except the weakest one, d, were observed. Because of their small separation compared to the Doppler width, components a and b were not resolved. A photograph of the spectrogram is shown in Fig. 2.

From measurement of the interval c-e we obtain $A(^4P_{1/2}) = 166(4)\times10^{-3}$ cm^{-1}, where $A(^4P_{1/2})$ is the $M1$ hfs interaction constant. With the assumption of negligible hfs anomaly and use of the known ^{209}Bi magnetic moment,[2] it follows[10] from the above value that $A(^4S_{3/2}) = 15.1(4)\times10^{-3}$ cm^{-1}

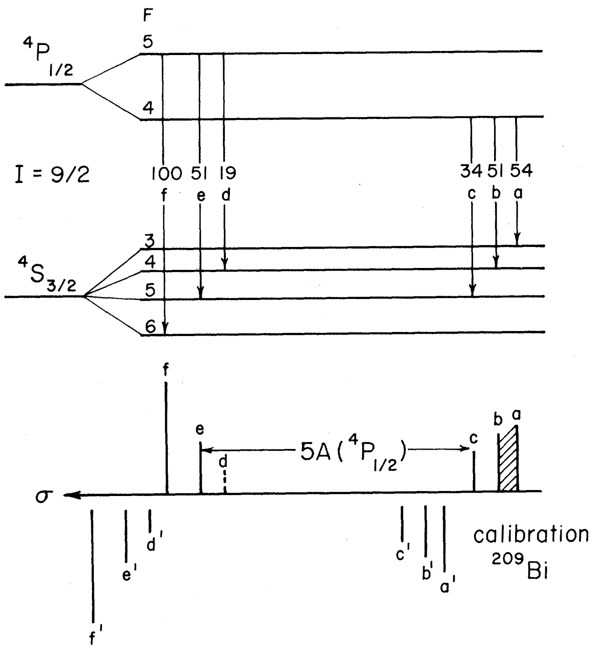

FIG. 1. Hyperfine structure of the $6p^27s\ ^4P_{1/2}$-$6p^3\ ^4S_{3/2}$ 3067-Å resonance line of ^{205}Bi. The relative intensities of the hfs components, with the maximum equal to 100, are given.

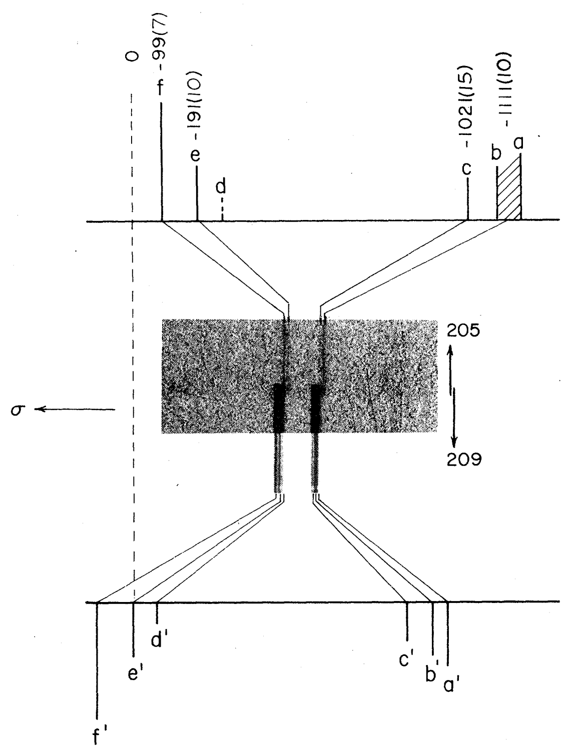

FIG. 2. Spectrogram of the ^{205}Bi 3067-Å line. The numbers above the component markers are the measured positions, in units of 0.001 cm^{-1}, relative to the e' line of the ^{209}Bi calibration spectrum. For the unresolved components a and b, the midpoint is given. The weakest component, d, was not observed. The center of gravity of ^{209}Bi is displaced from ^{205}Bi by the isotope shift of 0.192(14) cm^{-1} toward the higher wave-number side. The reproduction of the spectrographic plate fails to show some of the weak but readily measurable lines and decreases the apparent resolution. A shorter exposure was used in reproducing the lower portion of the ^{209}Bi calibration.

and $\mu(^{205}\mathrm{Bi}) = 4.13(11)\mu_N$. Measurements of the interval e'-f (Fig. 1) give a value $192(14)\times 10^{-3}$ cm^{-1} for the ^{205}Bi-^{209}Bi isotope shift; ^{205}Bi lies at the lower wave-number side, as would be expected for a predominantly volume-dependent shift involving the 7s electron in the upper state.

^{207}Bi.—We direct attention to two features which can be seen in the published photograph of the spectrogram that we obtained in our earlier experiment[3] for ^{207}Bi: (1) There is a definite shift (isotope shift) between the ^{207}Bi and ^{209}Bi hfs patterns; (2) the ^{207}Bi lines have just the width expected from Doppler broadening. (The slightly greater width of ^{207}Bi lines as compared to those of ^{209}Bi reference is expected from the higher operating temperature of the radioactive-isotope lamp.)

From the above it is apparent that there can be no appreciable ^{209}Bi contamination in the ^{207}Bi lamp in our earlier experiment. A more detailed analysis of the line shape by Winkler and Müller[11] leads to the conclusion that if any ^{209}Bi impurity were present, the amount would be at most a few percent.

One might also conceive that the amount of ^{207}Bi in the lamp, as monitored by the radioactivity, was insufficient to produce the observed bismuth hfs, and that what was recorded was actually ^{209}Bi shifted appropriately by a change in the spectrograph geometry which occurred at a time between the two separate exposures. The latter supposition, however, is not supported by the fact that ^{209}Bi reference spectra were recorded before and after the ^{207}Bi exposure, and no such shift was observed, and because of results from a second spectrogram (Fig. 3). This spectrogram was obtained with a lamp containing, in addition to ^{207}Bi, an estimated 20–25% ^{209}Bi. The presence of ^{209}Bi in appreciable amounts allowed the simultaneous recording of ^{207}Bi and ^{209}Bi hfs patterns. This spectrogram, in which hfs components of both isotopes are individually observable, clearly negates the possibility of an instru-

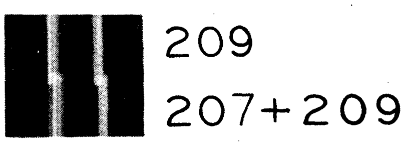

FIG. 3. Spectrogram of the ^{207}Bi 3067-Å line showing resolved ^{209}Bi contamination (component f', identified in Fig. 2) in the radioactive ^{207}Bi lamp. The weak component c' was also observed, but reproduced only in lower contrast photographs (not shown). The use of an image intensifier decreased somewhat the spectrograph resolution. The ^{209}Bi reference spectrum is also shown.

mentally produced shifted pattern, and in addition confirms the results of our earlier ^{207}Bi hfs measurements.

The magnetic moment value found by Johnston, Kaplan, and Stone would increase the separation of the two outer components of the ^{207}Bi hfs pattern, shown in Fig. 3 of Ref. 3, by $\approx 13\%$, which is some 4 times the Doppler width. This is contrary to the spectroscopic data, even by inspection. A small part of the discrepancy between the spectroscopic and nuclear orientation results may be attributed to the hfs anomaly. This affects measurements of μ in both experiments. In fact, we do not expect this effect to be significant here. For example, Kaplan *et al.*[12] calibrated their hyperfine field, for nuclear orientation, with the use of $\mu(^{206}\mathrm{Bi})$ obtained from ^{206}Bi hfs measurements[7] and $\mu(^{209}\mathrm{Bi})$ without hfs anomaly correction. A model calculation shows this to be of the order of 0.2%.[13] In the optical spectroscopic work the A values are measured directly. The extraction of the magnetic moments is done with reference to $\mu(^{209}\mathrm{Bi})$, a procedure that also involves the hfs anomaly correction. For ^{207}Bi-^{209}Bi, this is estimated to be somewhat smaller than, but of the same order of magnitude as, the above hfs anomaly in the nuclear-orientation case.

A more general and serious problem in nuclear-orientation experiments appears to be that of control of specimen preparation and consequently that of consistent hyperfine-field determination.[12,14] It is thus found that results from successive experiments of this type can vary among themselves by some 10 to 30%.[14,15]

In analyzing the results, we note first that the large discrepancy ($\approx 1.46\mu_N$) between the experimental and single-particle values of the magnetic moment of ^{209}Bi was reduced substantially by the configuration-mixing calculations.[16,17] The use of the simplest set of parameters and a δ-function internucleon interaction[17a] leads to a correction of $0.68\mu_N$ when one considers the first-order perturbation contributions that result from the breakup of the paired $(1h_{11/2})^{12}$ protons and $(1i_{13/2})^{14}$ neutrons. The use of more realistic parameters[17b] leads to a correction $\approx 0.2\mu_N$ higher, i.e., a calculated magnetic moment of $\approx 3.5\mu_N$. The remaining $\approx 0.58\mu_N$ constituted for long a serious and unexplainable discrepancy. There were refinements of the shell-model calculations and realistic nuclear forces were used.[18] A small part could be ascribed to quenching of the intrinsic nucleon moments, but it was not until the rediscovery[19] of the importance of orbital-moment quenching[20] that the remaining discrepancy was resolved. In recent calculations Arima and co-workers find that one-pion exchange contributes to the magnetic moment $\delta\mu^{\mathrm{mes}} = \delta g_l^{\mathrm{mes}} l$, where $\delta g_l^{\mathrm{mes}} = 0.112$. This is important in ^{209}Bi for which $l = 5$, hence $\delta\mu^{\mathrm{mes}} = 0.56$, and one finally finds $\mu^{\mathrm{calc}} \approx \mu^{\mathrm{expt}}$ for this doubly magic-plus-one nucleus. Because the isotopic variations of $\delta\mu^{\mathrm{mes}}$ are expected to be small,[19] the calculated $\mu(^{207}\mathrm{Bi})$ would differ from $\mu(^{209}\mathrm{Bi})$ essentially through the difference in the configuration-mixing contribution. From pairing-energy considerations, we assume that a $3p_{1/2}$ neutron pair is removed in going from ^{209}Bi to ^{207}Bi. This allows the further excitation of the $(3p_{3/2})^4$ neutrons. We thus calculate,[17a] in a manner similar to that for ^{209}Bi, a magnetic moment for ^{207}Bi of $\mu = 4.18\mu_N$, *i.e.*, $0.12\mu_N$ larger than the calculated $\mu(^{209}\mathrm{Bi})$. For ^{205}Bi, we assume that we remove in addition a $(3p_{3/2})^2$ neutron pair, which leads to a value for $\mu(^{205}\mathrm{Bi})$ of $4.13\mu_N$. On the basis of these calculations, substantial variations among the magnetic moments of these three bismuth isotopes are not expected. This is in agreement with our findings.

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Comments on Weak Neutral Vector Mesons and Charge Asymmetry in $e^+e^- \to \mu^+\mu^-$†

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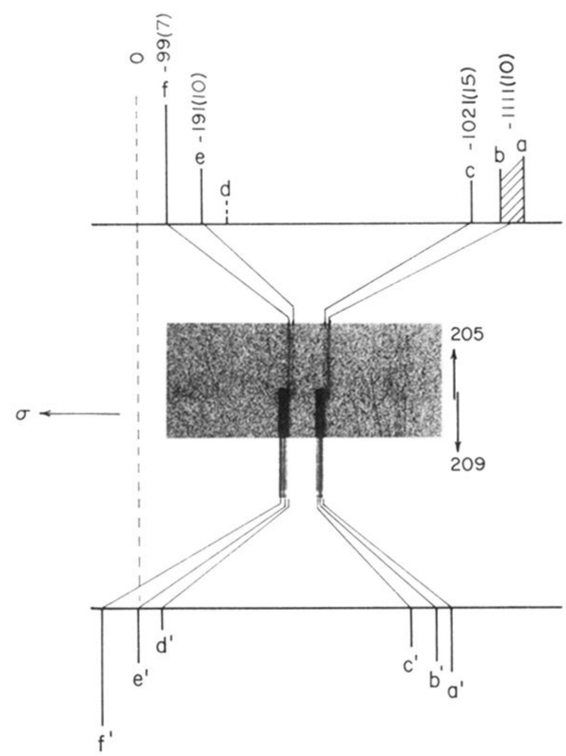
We comment on the forward-backward asymmetry in the reaction $e^+e^- \to \mu^+\mu^-$ due to the possible existence of parity-nonconserving weak neutral interactions. Estimates are given for the possibilities that such an interaction is mediated either by a very massive vector boson or by the recently discovered $J(3105)$ or $\psi'(3695)$ particles.

As a result of the discovery of weak neutral currents[1] and the development of gauge theories,[2] the search for parity nonconservation in neutral weak processes has received renewed interest.[3-5] Furthermore, the recent discovery of the $J(3105)$[6,7] and $\psi'(3695)$[8] particles offers the possibility that these particles might be the bosons mediating such interactions. In this note, we suggest a search for parity-nonconserving effects in the reaction $e^+e^- \to \mu^+\mu^-$ in the J and ψ' regions and, if these particles do not mediate parity-nonconserving interactions, in the continuum region. The latter case can provide us with a rather stringent bound on the strength of the interaction in addition to those obtained in Ref. 5.

In the presence of parity-nonconserving, but time-reversal-invariant, interactions, charge-conjugation invariance is also violated. The interaction Hamiltonian for the leptons can be written as

$$\mathcal{H} = e\sum_l \bar\psi_l\gamma_\mu\psi_l A^\mu + \sum_i\sum_l g_{il}\bar\psi_l\gamma_\mu(a_{il}+ib_{il}\gamma_5)\psi^l W_i^{\mu} + \sum_i (g_{i\nu}/\sqrt{2})\bar\psi_\nu\gamma_\mu(1+i\gamma_5)\psi_\nu W_i^{\mu}, \quad (1)$$



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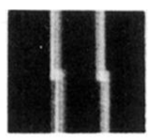

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