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**DIRECT MEASUREMENT OF THE MAGNETIC
MOMENT OF PLUTONIUM-239†**

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The magnetic moment of Pu^{239} has been the subject of experimental work for about a decade. The original measurement was performed by Bleaney et al.¹⁾ in 1954. They concluded that $\mu_1(239)$ equals $\pm 0.4(2)$ nm on the basis of paramagnetic resonance studies. An atomic-beam measurement by Hubbs et al.²⁾ of the hyperfine structure in the 3F_1 state of the free atom yielded $\mu_1(239) = \pm 0.02$ nm with the assumption of pure Russell-Saunders coupling. Subsequently several determinations based on optical hyperfine structure were made, particularly by the Bellevue group (Refs. 3, 4, and 6). The results of all these measurements are summarized in Table I. It should be emphasized that all of these values of $\mu_1(239)$ are inferred from measurements of magnetic dipole hyperfine constants A according to the relation $\mu_1(239) = IJ \frac{A}{H_N}$, where H_N is the magnetic field at the nucleus, I is the nuclear spin and equals $1/2$, and J is the electronic angular momentum. Hence all of these determinations rest on assumptions concerning the magnetic field at the nucleus.

Recently, an analysis of the hyperfine structures (hfs) of the states arising from the 3F level was undertaken by Bauche and Judd.⁷⁾ These authors showed that the A values of these states could be understood if contributions to H_N arising from core polarization and the breakdown of Russell-Saunders coupling were taken into account. The size of the Casimir correction factors indicated that relativistic effects are negligible. They

concluded that $\mu_I(239) = 0.17 (0.04) \text{ nm}$. Armstrong's recent calculations of relativistic effects in the hyperfine structure of these states are based on a Hartree-Fock central field.⁸⁾ He shows that these effects may be the dominant contribution to the hfs. However, they have the same J dependence as the core polarization and would not interfere with the fit of Bauche and Judd. Only a measurement of the hyperfine anomaly could decide whether core polarization or relativistic effects are dominant.

In this note we report the result of a direct measurement of $\mu_I(239)$ by the method of triple resonance in an atomic beam.⁹⁾ The atomic-beam flop-in method was employed and is described elsewhere.¹⁰⁾ For a hyperfine structure system of $I = 1/2$, $J = 1$, the normal flop-in transition, which we denote as a , has the quantum numbers $F = 3/2$, $m_F = 1/2 \leftrightarrow F = 3/2$, $m_F = -3/2$. The end hairpins were always set at the frequency corresponding to the center of the resonance line of a . The hyperfine constants determining these frequencies are taken from the data of Hubbs et al.²⁾ The two transitions that are sensitive to the nuclear moment we denote by α and β and have the quantum numbers $F = 3/2$, $m_F = 1/2 \leftrightarrow F = 3/2$, $m_F = 3/2$ and $F = 3/2$, $m_F = -3/2 \leftrightarrow F = 1/2$, $m_F = -1/2$, respectively. These transitions are of the type $\Delta m_I = \pm 1$ and $\Delta m_J = 0$ in high field, and in the high-field limit the resonant frequencies are given by

$$\nu = \pm A + g_I \mu_0 H$$

where μ_0 is the Bohr magneton and H is the applied field. Therefore the field dependence of the resonant frequency is a precise, direct measure of the nuclear moment.

When the frequency applied to the center hairpin corresponds to the resonant frequency for either of these transitions, the detector registers an increase in signal.

The data were analyzed as follows: we combined the observed resonances of Hubbs et al. with our triple-resonance data and on the IBM-7094 made a least-squares fit according to the Hamiltonian

$$\mathcal{H} = A(\underline{I} \cdot \underline{J}) - g_J \mu_0 \underline{J} \cdot \underline{H} - g_I \mu_0 \underline{I} \cdot \underline{H} \quad (2)$$

The data of Hubbs et al. essentially determine the values of A and g_J , whereas our data fix the value of g_I . The value obtained in this way is

$$\mu_I(239) = +0.200(4) \text{ nm} \quad .$$

where a correction for diamagnetic shielding has been made. The data fit is shown in Table II. The results for the triple resonance only are given.

Our value of $\mu_I(239)$ is within the limits of error set by Bauche and Judd. We are currently trying to extend our measurements to the isotope Pu^{241} . If the hypothesis of large amounts of core polarization is correct, then a large hyperfine anomaly should exist in these isotopes.

The value of the $\mu_I(239)$ has also been calculated by Mottelson and Nilsson,¹¹⁾ on the basis of the Nilsson model, to be -0.1 nm. Recently Rasmussen and Chiao¹²⁾ have recalculated this moment using "quenched" g factors and obtained -0.06 nm. Hence there is a discrepancy in sign between the theoretical and experimental values.

FOOTNOTES AND REFERENCES

† Work supported by the U. S. Atomic Energy Commission.

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Table I. Prior measurements of $\mu_1(239)$.

| Group | Nuclear moment values (nm) |
|---------------------------------------|----------------------------|
| Bleaney et al. ^a | 0.4 (2) |
| Hubbs et al. ^b | 0.021 |
| Champeau and Gerstenkorn ^c | 0.27(6) |
| Gerstenkorn ^d | 0.24(6) |
| Korostyleva ^e | 0.15(4) |
| Bauche et al. ^f | 0.16(2) |

a) See reference 1).

b) See reference 2).

c) See reference 3).

d) See reference 4).

e) See reference 5).

f) See reference 6).

Table II. Fit to the Hamiltonian

$$3C(\text{mc}) = 5.139 \underline{I \cdot J} - 1.4973 \mu_0 \underline{J \cdot H} + 2.15 \times 10^{-4} \mu_0 \underline{I \cdot H}.$$

| Transition | H(G) | Frequency (Mc) (ν_{exp}) | Residual (Mc) ($\nu_{\text{theory}} - \nu_{\text{exp}}$) |
|------------|-----------|------------------------------------------|---------------------------------------------------------------|
| a | 10.00(5) | 4.445(15) | 0.004 |
| b | 10.00(5) | 5.688(15) | -0.003 |
| a | 25.00(4) | 4.865(15) | -0.003 |
| b | 25.00(4) | 5.385(15) | -0.004 |
| a | 155.00(1) | 5.050(15) | -0.002 |
| b | 155.00(1) | 5.220(15) | -0.006 |
| a | 430.00(4) | 4.997(10) | -0.002 |
| b | 430.00(4) | 5.276(10) | -0.007 |
| a | 720.00(7) | 4.945(20) | 0.004 |
| b | 720.00(7) | 5.360(20) | -0.005 |
| a | 720.00(7) | 4.944(3) | 0.000 |
| b | 720.00(7) | 5.366(3) | 0.004 |

