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# RELATIVISTIC EFFECT ON MAGNETIC MOMENTS OF NEGATIVE MUONS BOUND TO HIGH-Z NUCLEI*

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## ABSTRACT

The g factors of the negative muons bound to Zn, Cd, and Pb nuclei have been determined. The observed values after the corrections for the internal fields have shown substantial deviations from the free-muon g factor: $(g_{free}-g)/g_{free}$ is $(1.1 \pm 0.8)\%$ for Zn $(2.2 \pm 1.5)\%$ for Cd, and $(5.0 \pm 2.2)\%$ for Pb. These shifts are in good agreement with the relativistic binding corrections for finite-size nuclei calculated by Ford et al.

In 1928, following the Dirac theory of the electron, Breit[1] predicted that the electron in a K-shell orbit must possess a g factor different from the free-electron value ($g_{free} = -2$) due to its relativistic motion. He gave the following estimate for a point nucleus of charge Ze:

$$\frac{g_{free} - g}{g_{free}} = \frac{2}{3} \left(1 - \sqrt{1-\alpha^2 Z^2}\right) \approx \frac{1}{3} (\alpha Z)^2 = \frac{1}{3} \left(\frac{\bar{v}}{c}\right)^2 . \qquad (1)$$

More general expressions were derived by Margenau.[2] While this effect was not examined in ordinary atoms because of the lack of techniques to measure the g factors of deeply bound electrons, it is straightforward to study this effect in the ground states of muonic atoms which consist of one muon in the $s_{1/2}$ state and a zero-spin nucleus. The first observation of the Breit effect was done in 1961 by Hutchinson et al.[3] who determined the g factors of the bound muons in light elements up to Z = 16. Their values agreed well with the estimate (1). At the same time Ford et al.[4] made a comprehensive calculation of all the possible effects on the bound-muon g factor. The largest is the binding correction due to the Breit effect, which, however, shows considerable deviation from the point nucleus estimate (1) starting around Z = 16, because of the nuclear finite size. The data in Ref. 3 favored the theoretical values of Ford et al. though the finite-size corrections for those light nuclei are small. It is obviously interesting to extend such measurements to heavier nuclei, where greater effects are expected, but it becomes exceedingly difficult to determine the g factors precisely because of the shorter lifetimes and the smaller yields of decay electrons. We have been measuring the negative muon spin precessions in various heavy elements, and this is the first report on the bound-muon g factors for Zn (Z = 30), Cd (Z = 48), and Pb (Z = 82). The μSR (muon spin rotation) method was employed, in which the rotation of the angular asymmetry of decay electrons associated with the Larmor precession of the muon spin in the presence of an external transverse field is observed time-differentially. The diamagnetic metals of Zn, Cd, and Pb were used as the targets, for which Ignatenko et al.[5] already observed spin precessions but obtained no accurate precession frequencies.

We used a muon beam in the so-called meson cave at the 184-in. synchrocyclotron at Lawrence Berkeley Laboratory. Negative pions were produced at the internal Be target, and those of 190 MeV/c momentum entered an 8-ft-long iron collimator (so-called meson wheel) through the fringing field of the cyclotron magnet. Decay-in-flight muons as well as pions and electrons of this momentum were then bent by 35° through a bending magnet. At the entrance of the counter-target assembly the beam was defined by a 5.7-cm-high by 7.6-cm-wide lead-copper collimator. The very intense electrons acted as a contaminant in the beam and contributed to a serious increase of background with a 20-MHz frequency component in the μ-e time spectrum; they were removed considerably by placing a 6-mm-thick (about one radiation length) lead absorber at the entrance of the meson wheel. A 30-cm polyethylene absorber was used so as to stop muons in the target. Unfortunately, many muons were produced before entering the meson wheel, and they had poor polarization. We selected the forward-decaying muons which had momenta just above 190 MeV/c, and thus obtained muons of about 60% polarization.

A target of 6.3 cm height by 7.6 cm width by ~ 8 to 9 g/cm$^2$ thickness was placed at the center of an iron-core magnet (9-in. Varian). An external magnetic field was applied perpendicular to the beam direction (6.829 kOe for Zn and Cd and 9.382 kOe for Pb). The gap of the magnet was 7.6 cm, and the field inhomogeneity over the target area was less than 0.1%. The decay electrons in the forward direction were detected in order to observe spin precession.

The counter system is shown in Fig. 1. The counter telescope and electronics logic were essentially the same as those used for the $\mu^+$ experiment at LBL by Crowe et al.[6] The fast logic was as follows:

$$\begin{aligned} \text{"stopped } \mu\text{"} &= B\cdot M\cdot S1\cdot \overline{(S2X+A1+A2)}, \\ \text{"decay e"} &= S2X\cdot S2\cdot E\cdot S3\cdot \overline{(B+M+S1+A1+A2)}\ . \end{aligned} \tag{2}$$

The time interval between a stopped muon and decay electron was measured by means of a digital counter (Hewlett-Packard Model 5360A) to a precision of 0.1 nsec and this counter was connected to a PDP-15 computer. The timing among the plastic counters was adjusted so as to measure a time spectrum as early as 10 nsec after the muon stopped. The overall time resolution of the system was 0.5 nsec. The stopped-muon rate in the target was $6\times 10^3$ sec$^{-1}$, and the net event rate of decay electrons from the target was about 20 sec$^{-1}$. The "decay e" logic events, however, involved additionally those which had no time relation with the stopped-muon event and thus yielded substantial accidental coincidences.

The time spectrum of decay electrons was taken from t = 0.02 to t = 5.5 μsec. The observed spectrum showed a fast decay component (due to Zn, Cd, and Pb), a long-lived component (supposedly due to C and O from the surrounding counters), and a constant background. In the presence of the field the Larmor precession gives the following time spectrum:

$$N(t) = N_0 \exp(-t/\tau_0)[1 - A_0 \cos(\omega_0 t+\phi_0)] + N_1 \exp(-t/\tau_1)[1 - A_1 \cos(\omega_1 t+\phi_1)] + C, \qquad (2)$$

where "0" and "1" refer to the fast and slow components, respectively. The observed lifetimes $\tau_0$ are 159.8 ± 1.5, 92.1 ± 0.8, and 78.0 ± 1.0 nsec for Zn, Cd, and Pb, respectively; $\tau_1$ was about 1.6 μsec for all the cases, and $N_1/N_0$ was nearly 0.1.

It was not easy to determine $\omega_0$ accurately, since the background component involved a frequency $\omega_1$ which was close to $\omega_0$, and the amplitude $A_0$ was not large. Our procedure was as follows. First, we analyzed data for graphite targets, which were taken before and after each run in order to make sure the system was all right. These data yielded an amplitude of 0.042 and phases of 0.0 ± 0.3 radian at $H_0 = 9.382$ kOe and -0.45 ± 0.2 radian at $H_0 = 6.829$ kOe, which are consistent with our counter configuration. Second, we chose $\phi_0$ and $\phi_1$ to be equal to the phase for the graphite runs. The slow component showed damping of $A_1$ between t = 0.5 and 5.5 μsec, and so we took $A_1$ at $t \approx \tau_0$ to be 0.03 ± 0.01. The results of the $\chi^2$ fitting of the data are presented in Table I. The asymmetry $A_0$ over the time range of the lifetime was about 2 - 2.5% for Zn and Pb and 3 - 4% for Cd. These values are smaller than the previously known values.[5]

Possible corrections on the effective field at the bound muon are for the Knight shift and the diamagnetic shielding. The muonic atom with a nuclear charge Ze behaves like an impurity nucleus of atomic number $Z' = Z-1$ (strictly speaking, this may not be true, since the muonic atom has a substantially extended spatial distribution, but for the present purpose it should be all right). The Knight shift for the impurity Tl atom in the metallic Pb is experimentally known,[7] but for the other cases we estimated from the known Knight shifts for Ag in Ag and Cu in Cu. These values are presented in column 4 of Table I. As to the diamagnetic corrections, we adopted the theoretical values of Feiock and Johnson,[8] as listed in column 5. The experimental g factors (percentage deviation from the free-muon value) thus corrected are entered in column 6.

These final values are compared with the theoretical values of Ford et al.[4] in Fig. 2. The dotted curve is the original Breit correction for the point nucleus, the solid curve is the relativistic correction for the finite-size nucleus, and the broken curve includes the upper limit to the magnetic polarization effect estimated by Ford et al., which is one order of magnitude smaller than the relativistic correction. The present experimental values are in good agreement with the theoretical values of Ford et al., and thus demonstrated for the first time the presence of the relativistic effect in the high-Z region, where the finite-size effect of the nucleus is appreciable. The bound-muon g factors, if determined more accurately, would provide information on the nuclear magnetic polarizability as well as on solid states, but the present data are not good enough to discuss such small effects.

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## Footnote and References

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Table I. Summary of the present experiment.

| Target | Observed frequency, f (MHz) | $\frac{f_0 - f}{f_0}$[a] (%) | Corrections | | $\frac{g_{\text{free}} - g}{g_{\text{free}}}$[c] (%) |
|---|---|---|---|---|---|
| | | | Knight shift (%) | Diamagnetic shielding[b] (%) | |
| Zn | 91.6 ± 0.7 | 1.04 ± 0.65 | 0.35 ± 0.10[d] | -0.26 | 1.14 ± 0.76 |
| Cd | 90.7 ± 1.3 | 2.01 ± 1.41 | 0.77 ± 0.10[d] | -0.56 | 2.21 ± 1.50 |
| Pb | 121.2 ± 2.8 | 4.68 ± 2.20 | 1.93 ± 0.01[e] | -1.63 | 4.96 ± 2.20 |

[a] The frequency $f_0$ is the free-muon frequency expected at the external field used in the present experiment; $f_0$ (for Zn and Cd) = 92.56 ± 0.06 MHz and $f_0$ (for Pb) = 127.14 ± 0.10 MHz.

[b] Ref. 8.

[c] The g factors corrected for the Knight shifts and diamagnetic shieldings are used.

[d] The Knight shift of impurity B in material A was calculated from the Knight shift of B in B using the equation of

$$\frac{K(\text{B in A})}{K(\text{B in B})} \approx \frac{\chi_p(A)}{\chi_p(B)} = \left(\frac{k_F^B}{k_F^A}\right)^2 \cdot \frac{N_A}{N_B}$$

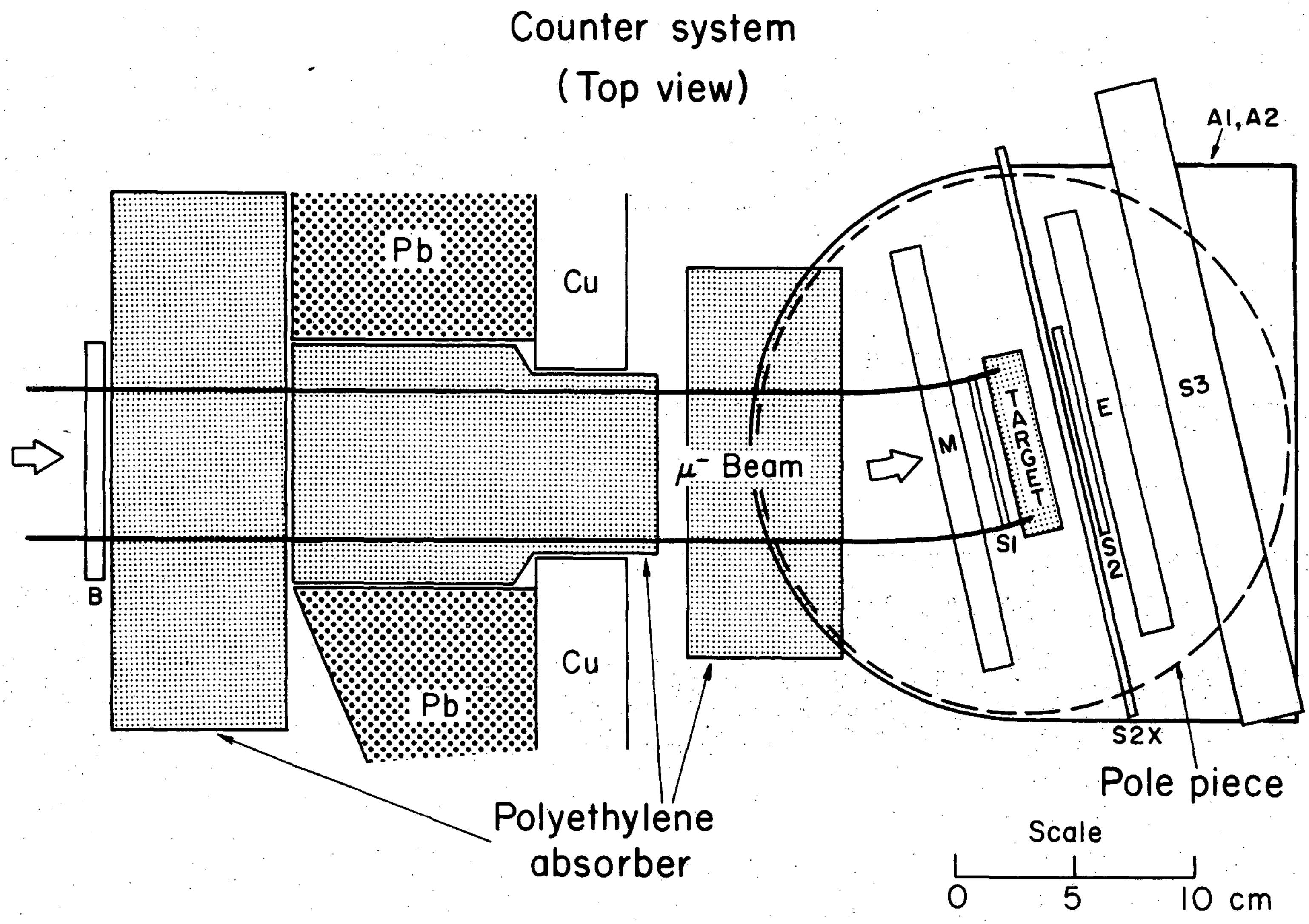
(see Ref. 7), where N and $k_F$ are the number of valencies and Fermi momentum, respectively. The free-electron model was assumed for the last equation. The Knight shifts of Cu in Cu (0.23%) and Ag in Ag (0.52%) have been known already [L. E. Drain, Met. Rev. 12, 195 (1967); D. J. Kahan, private communication], and thus the Knight shifts of Cu in Zn and Ag in Cd could be estimated. A possible error in the estimation of the above equation was added.

[e] This value is the experimental value of dilute Tl atoms in a Pb metal, taken from Ref. 7.

## Figure Captions

Fig. 1. Counter system in the present experiment. All the counters were plastic scintillators connected to RCA 8575 phototubes through photoguides. These counters were placed between two pole pieces of the 9-in. Varian magnet with its gap of 7.6 cm. The A1 and A2 counters (thickness is 3 mm) were fixed to the surfaces of the pole pieces in order to eliminate the background from the iron cores. The height of the counters—except B, A1, and A2—was 6.3 cm. The size of the B counter was 10×10 cm.

Fig. 2. Relativistic effect (or binding effect) on the g factor of bound muons. The dotted curve shows the relativistic correction for a point nucleus (Ref. 1). The solid curve shows the calculated values by Ford et al. (Ref. 4) where the finite-size effect of the nucleus is taken into account. The difference between the solid and broken curves is the nuclear polarization effect calculated by Ford et al. The experimental data after the correction for the Knight shift and the diamagnetic shielding are plotted.



XBL 741-2155

Fig. 1.

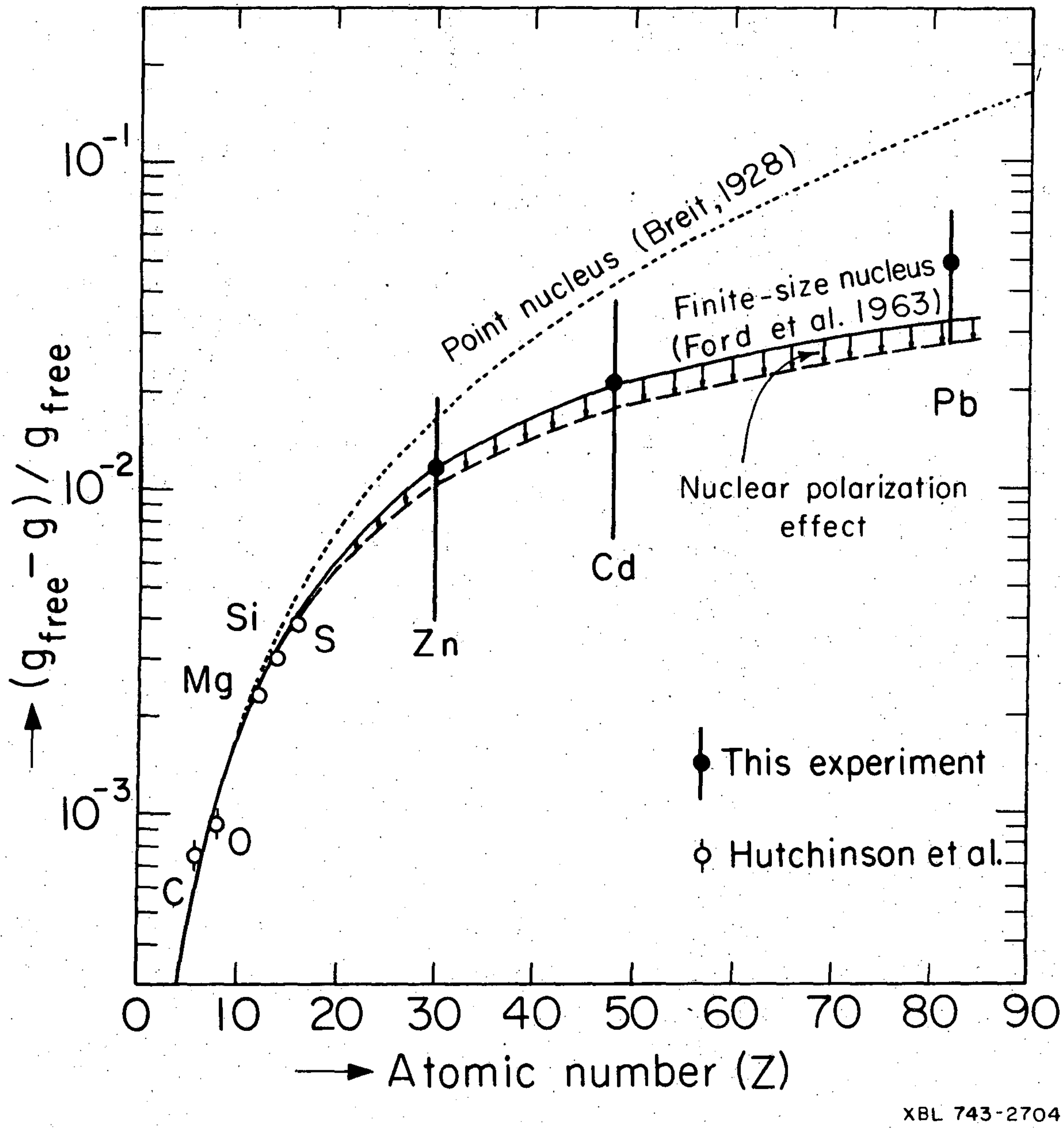

Point nucleus (Breit, 1928)
Finite-size nucleus (Ford et al. 1963)
Nuclear polarization effect
Pb
Cd
Zn
S
Si
Mg
O
C
This experiment
Hutchinson et al.
$10^{-1}$
$10^{-2}$
$10^{-3}$
$(g_{free} - g)/g_{free}$
0
10
20
30
40
50
60
70
80
90
Atomic number (Z)
XBL 743-2704

Fig. 2.

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