# Atomic $g_J$ Values for Neon and Argon in Their Metastable $^3P_2$ States; Evidence for Zero Spin of $_{10}Ne^{20}$†

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The gyromagnetic ratios of neon and argon in their metastable $^3P_2$ states have been measured by the atomic beam magnetic resonance method. The results are $g_J(\mathrm{Ne},{}^3P_2)=1.500888\pm0.000005$ and $g_J(\mathrm{A},{}^3P_2)=1.500964\pm0.000008$, in agreement with the less precise optical spectroscopic measurements. Theoretical values, including radiative and relativistic effects, are $g_J(\mathrm{Ne},{}^3P_2)=1.50088$ and $g_J(\mathrm{A},{}^3P_2)=1.50095$, in good agreement with the experimental values. In addition, the Zeeman transition frequency for neon has been measured as a function of magnetic field to obtain evidence that the magnetic moment of $Ne^{20}$ is less than $4\times10^{-4}$ nuclear magneton and hence that the spin of $Ne^{20}$ is probably zero.

## INTRODUCTION

It is now well known that metastable states of rare gas atoms can be produced in a discharge or by crossed-beam electron bombardment and can be detected by Auger electron ejection from a metal so as to make possible studies of these atomic states by the atomic beam magnetic resonance method.[1] One purpose of this paper is to report precision measurements of the Zeeman effect of neon and argon in their metastable $^3P_2$ atomic states and their comparison with theoretical calculations.

A second purpose is to contribute evidence that the spin of $Ne^{20}$ is zero as is expected for a nucleus with even $A$ and even $Z$. It should be noted that direct experimental information on the nuclear spins of the noble gas atoms is rather incomplete because the ground state of these atoms is a $^1S_0$ state for which there is no hyperfine structure, and because the noble gases do not readily form stable molecules which would allow the determination of their nuclear spins by optical band spectroscopy. From studies of the Zeeman effect in the $^3P_2$ metastable state, an upper limit can be deduced for the hyperfine structure interaction constant which in turn implies an upper limit for the nuclear magnetic moment. This latter value will be so small as to make the existence of a spin value other than zero most unlikely. Short preliminary reports on the experimental results have already been made.[2]

## THEORY OF THE EXPERIMENT

Neon and argon have metastable states with electron configurations $(2p)^5\,3s$ and $(3p)^5\,4s$, respectively, and with total electronic angular momentum quantum number $J=2$. From the theory of configurations of almost-closed shells, it follows that the Zeeman effect of these states is equivalent to that of the corresponding configuration which consists of a single $p$ hole and an $s$ electron. Since a state with $J=2$ can be formed from this equivalent configuration by only one coupling scheme, the state can be regarded as a $^3P_2$ state in Russell-Saunders terminology, and the Landé formula gives $g_J=1.5$. Corrections to this $g_J$ value due to impurity of the atomic state and due to relativistic and radiative effects will be discussed later.

In order to obtain evidence as to the nuclear spin of $Ne^{20}$ from studies of the Zeeman effect of the $^3P_2$ state, the following considerations are useful. If $Ne^{20}$ had a nonzero spin, there would be a magnetic hyperfine structure interaction of the form $a\mathbf{I}\cdot\mathbf{J}$ which would result in a splitting of the $J=2$ level into hyperfine levels designated by the total atomic angular momentum quantum number $F$, where $\mathbf{F}=\mathbf{I}+\mathbf{J}$. At weak magnetic fields where $g_J\mu_0H\ll a$, the atomic $g$ value would be given by

$$g_F=g_J\frac{F(F+1)+J(J+1)-I(I+1)}{2F(F+1)}+g_I\frac{F(F+1)+I(I+1)-J(J+1)}{2F(F+1)}.$$

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[1] V. W. Hughes, G. Tucker, E. Rhoderick, and G. Weinreich, Phys. Rev. **91**, 828 (1953); G. Weinreich and V. W. Hughes, Phys. Rev. **95**, 1451 (1954); A. Lurio, C. W. Drake, V. W. Hughes, and J. A. White, Bull. Am. Phys. Soc. **3**, 8 (1958); H. Freidburg and H. Kuiper, Naturwiss. **44**, 487 (1957); G. M. Grosof, P. Buck, W. Lichten, and I. I. Rabi, Phys. Rev. Letters **1**, 214 (1958).

[2] G. Weinreich, G. Tucker, and V. W. Hughes, Phys. Rev. **87**, 229 (1952); C. W. Drake, V. W. Hughes, and A. Lurio, Bull. Am. Phys. Soc. **2**, 37 (1957); A. Lurio, C. W. Drake, V. W. Hughes, and J. A. White, Bull. Am. Phys. Soc. **3**, 9 (1958).

Transitions could be induced satisfying the selection rule $\Delta m_F = \pm 1$, in which $m_F$ is the magnetic quantum number associated with $F$, and would have the frequency $g_F\mu_0 H/h$. This frequency would in general be markedly different from the frequency $g_J\mu_0 H/h$ in the case where no nuclear spin exists.

At strong magnetic fields where $g_J\mu_0 H \gg a$, the energy levels would be given by

$$W = (g_J m_J + g_I m_I)\mu_0 H + a m_I m_J,$$

in which $m_J$ and $m_I$ are the magnetic quantum numbers associated with $J$ and $I$. The observable transitions satisfy the selection rules $\Delta m_J = \pm 1$, $\Delta m_I = 0$, and the transition frequencies are

$$\nu = g_J\mu_0 H/h + a m_I/h.$$

There would thus be a cluster of $2I+1$ equally intense lines about the frequency $g_J\mu_0 H/h$ with spacing $a/h$.

At intermediate magnetic fields where $a/g_J\mu_0 H < 1$, the transition frequency can be developed in powers of the parameter $a/g_J\mu_0 H$:

$$\nu = \frac{g_J\mu_0 H}{h}\left[1 + m_I\left(\frac{a}{g_J\mu_0 H}\right) + K\left(\frac{a}{g_J\mu_0 H}\right)^2 + \cdots\right], \quad (1)$$

where $K$ is given by

$$\begin{aligned} K(m_J m_I \leftrightarrow m_J' m_I') = {} & \tfrac{1}{2}I(I+1)(m_J - m_J') \\ & - J(J+1)(m_I - m_I') + m_I m_J (m_J - m_I) \\ & - m_I' m_J' (m_J' - m_I'), \end{aligned}$$

and is of the order of unity. Hence, another method of discovering the effect of a nuclear moment is by observing the departure of the $\nu$ vs $H$ relationship from linearity, as expressed by the last term in (1). If no such departure from linearity is observed at a field $H$ with resolution $\overline{\Delta}\nu$, then

$$\frac{g_J\mu_0 H}{h}\left(\frac{a}{g_J\mu_0 H}\right)^2 < \overline{\Delta}\nu,$$

and, since in this case $\nu = g_J\mu_0 H/h$, it follows that $a/h < (\nu\overline{\Delta}\nu)^{\frac{1}{2}}$.

## APPARATUS, OBSERVATIONS, AND RESULTS

The principal apparatus used for the present measurements was the Yale atomic beam magnetic resonance apparatus previously used for the measurement of the $g_J$ value of helium in the $^3S_1$ state.[3] The early phase of the work was done at Columbia University.[4] Commercial neon and argon were used in the discharge tube at a pressure of a few tenths of a mm of Hg; the tube voltage and current were about 1000 v and 150 ma, respectively, supplied by a 400-cps generator. The only expected component in the beam with a magnetic moment is the metastable $^3P_2$ state since the ground and the $^3P_0$ metastable states have no magnetic moment. Detection of the metastable $^3P_2$ atoms is achieved by the Auger ejection of an electron from a wolfram wire upon which the metastable atom is incident.

The size of the detected beams of the noble gas atoms was observed to decrease rapidly with increasing atomic number. For helium a galvanometer deflection of 25 cm, for argon 3.5 cm, and for krypton 0.5 cm was observed.[5] In addition, the aluminum electrodes in the discharge tube sputtered more rapidly with increasing atomic number of the noble gas. For krypton the above two considerations made the observation of resonances impossible.

The radio-frequency power for the higher frequency measurements was obtained from a T85/APT-5 radar transmitter (coaxial line lighthouse tube oscillator) and for the lower frequency measurements from a General Radio type 805-$C$ signal generator. The static magnetic field in the transition region was measured by passing a helium beam through this region and measuring the Zeeman transition frequency in the $^3S_1$ state. The simplest method of identifying the refocussed beam of metastable $^3P_2$ atoms was by observation of a Zeeman transition.

With the Columbia apparatus[4] the frequency of the neon Zeeman transition was measured at fields of about 0.5 and 1.2 gauss which were as low values as could be

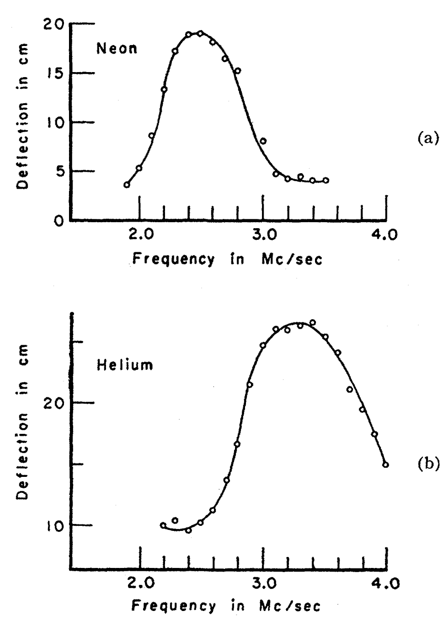


FIG. 1. Typical resonance curve for neon and helium at low magnetic field (1.2 gauss) taken with a single rf loop of 1.5 cm length.

[3] C. W. Drake, V. W. Hughes, A. Lurio, and J. A. White, Phys. Rev. **112**, 1627 (1958).

[4] G. Weinreich, G. Tucker, and V. W. Hughes, Phys. Rev. **87**, 229 (1952).

[5] Auxiliary experiments using crossed beam electron bombardment to produce the metastable atoms indicated that the observed decrease in metastable beam intensity with increase in $Z$ is due to reduced efficiency of production in the Wood's discharge tube.

used without losing space quantization. A typical neon line is shown in Fig. 1(a) for the 1.2-gauss field together with the $^3S_1$ helium line taken in the same field [Fig. 1(b)]. The linewidths of about 750 kc/sec and 1 Mc/sec for the neon and helium lines, respectively, were caused by inhomogeneity of the magnetic $C$ field due mostly to fringing of the $A$ and $B$ fields into the $C$ region. The center of the resonance for neon is chosen to within about 125 kc/sec which corresponds to $\bar{\Delta}\nu/\nu\sim 5\%$. A similar resolution was obtained at the 0.5-gauss field. Within this experimental accuracy, the observed $g$ value is 1.5 which is the theoretical value expected if the nuclear spin is zero. Hence, from Eq. (2) it is found that $a/h<250$ kc/sec.

With the Yale apparatus the frequencies of the neon and argon resonances were measured at a field of about 550 gauss using the method of separated oscillating fields. The separation between the rf loops was 2.2 cm and each loop was constructed from 3-mm wide copper ribbon placed inside a 5-mm wide shield. Typical resonance curves are shown in Figs. 2 and 3. The procedure used in observing the resonances was the same as that previously described[3] with alternate observations being made on helium and on neon or argon.

In the analysis of the data it is necessary to consider the quadratic Zeeman effect for Ne and A due to the admixture of the nearby $J=1$ states with the same electron configuration caused by the interaction with the external magnetic field. Since both Ne and A are characterized by an intermediate rather than a pure Russell-Saunders coupling scheme, significant admixture of both the $^3P_1$ and $^1P_1$ levels occurs. The energy dependence of the magnetic substates of the $^3P_2$ level, including the quadratic Zeeman effect, is given by

$$W(^3P_2,m_J)=W_0+g_J\mu_0Hm_J+(\mu_0H)^2\frac{(4-m_J^2)}{12}\left[\frac{\cos^2\theta}{W_0(^3P_2)-W_0(^3P_1)}+\frac{\sin^2\theta}{W(^3P_2)-W(^1P_1)}\right].$$

The quantity $\theta$ is a measure of the deviation from

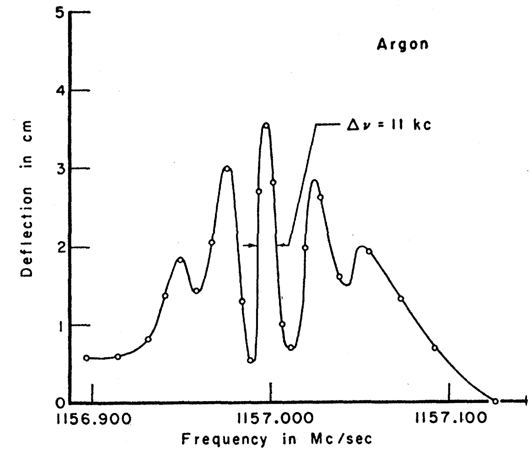


FIG. 2. A complete argon resonance curve taken with separated oscillating fields having a spacing of 2.2 cm between the rf loops.

Russell-Saunders coupling.[6] The quadratic frequency corrections to the various Zeeman transition frequencies for $H=550$ gauss are tabulated in Table I.

The observed resonance line actually arises as a superposition of transitions from all magnetic substates of the $^3P_2$ level by the method of separated oscillating fields. For a radio-frequency field of large amplitude, the transition probability is high and transitions to all four other magnetic sublevels must be considered for each magnetic sublevel. Due to the quadratic Zeeman effect, adjacent levels are not equally spaced. The complete theory of the line shape has not been worked out, but its qualitative features, including symmetry about the central peak, the existence of several interference peaks and their widths appear reasonable. It should be noted in particular (see Table I) that since the frequency

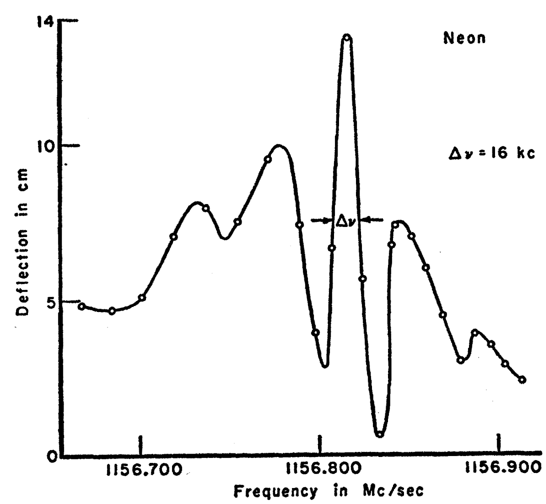


FIG. 3. A complete neon resonance curve taken with separated oscillating fields having a spacing of 2.2 cm between the rf loops.

TABLE I. Quadratic corrections to the Zeeman transitions of the $^3P_2$ states of neon and argon in frequency units for a magnetic field of 550 gauss.

| Quadratic correction to transition frequency between Zeeman levels for $H=550$ gauss | Neon $\theta=15°\,22'$ | Argon $\theta=32°\,16'$ |
|---|---|---|
| $\delta\nu(2,2\leftrightarrow 2,1)$, kc/sec | $-11$ | $-8$ |
| $\delta\nu(2,1\leftrightarrow 2,0)$, kc/sec | $-3.7$ | $-2.7$ |
| $\delta\nu(2,0\leftrightarrow 2,-1)$, kc/sec | 3.7 | 2.7 |
| $\delta\nu(2,-1\leftrightarrow 2,-2)$, kc/sec | 11 | 8 |

[6] See, for example, H. Kopfermann, *Nuclear Moments* (Academic Press, Inc., New York, 1958), p. 151.

TABLE II. Relativistic corrections to the magnetic moments of neon and argon. $g_J(\mathrm{Ne})=1.50088$; $g_J(\mathrm{A})=1.50095$.

| Type of correction | Neon $\Delta g\times 10^6$ | Argon $\Delta g\times 10^6$ |
|---|---|---|
| Breit-Margenau | −205 | −137 |
| Lamb | −29 | −27 |
| Orbit-orbit | −51 | −46 |
| Total | −285 | −210 |

shifts due to the quadratic Zeeman effect are of opposite sign for magnetic substates of opposite sign, the over-all line center is unaffected by the quadratic Zeeman effect.

The frequencies of the neon and argon transitions together with that of the helium transition taken at the same magnetic field can be used to determine $g_J(\mathrm{Ne},{}^3P_2)/g_J(\mathrm{He},{}^3S_1)$ and $g_J(\mathrm{A},{}^3P_2)/g_J(\mathrm{He},{}^3S_1)$. Using the previously determined value[3] of

$$g_J(\mathrm{He},{}^3S_1)=2(1.001119),$$

it is found that $g_J(\mathrm{Ne},{}^3P_2)=1.500888\pm0.000005$ and $g_J(\mathrm{A},{}^3P_2)=1.500964\pm0.000008$.

Further qualitative weight is lent to the conclusion that there is no hfs in neon by the fact that the intensity of the observed resonance line at $H=550$ gauss is approximately equal to the decrease in beam intensity observed when one of the focusing magnets is turned off, i.e., equal to the total refocussed beam. Had there been a resolved hfs, only a fraction of the beam (namely the appropriate hyperfine component) could undergo a transition at a particular frequency.

## CONCLUSIONS; COMPARISON WITH THEORY

Theoretical $g_J$ values for Ne and A in their ${}^3P_2$ states have been computed for comparison with the experimental values. The spin $g$ value of the free electron,[7] including radiative corrections to order $\alpha^2$, is taken as $g_s=2(1.0011596)$. Relativistic and diamagnetic corrections are calculated from the formulas developed for many-electron atoms.[8] Following the approach and notation of Abragam and Van Vleck,[8] we tabulate in Table II the different corrections to $g_J$ and give the details of the calculation in the Appendix. The breakdown of $LS$ coupling does not affect the $g_J$ value to within our experimental accuracy. Upon combining radiative, relativistic, and diamagnetic corrections we obtain the theoretical values

$$g_J(\mathrm{Ne},{}^3P_2)=1.50088,$$
$$g_J(\mathrm{A},{}^3P_2)=1.50095,$$

which are in excellent agreement with the experimental values.

[7] C. M. Sommerfield, Phys. Rev. **107**, 328 (1957); Ann. Phys. **5**, 26 (1958).
[8] W. Perl and V. Hughes, Phys. Rev. **91**, 842 (1953); W. Perl, Phys. Rev. **91**, 852 (1953); A. Abragam and J. H. Van Vleck, Phys. Rev. **92**, 1448 (1953); K. Kambe and J. H. Van Vleck, Phys. Rev. **96**, 66 (1954); F. R. Innes and C. W. Ufford, Phys. Rev. **111**, 194 (1958).

Since the hyperfine structure interaction constant of neon in the ${}^3P_2$ state has been found to be less than 250 kc/sec and since the hyperfine structure interaction constant of $\mathrm{Ne}^{21}$ in this ${}^3P_2$ state as well as the nuclear magnetic moment of $\mathrm{Ne}^{21}$ is known,[9] an upper limit to the magnetic moment of the $\mathrm{Ne}^{20}$ nucleus can be obtained. If a nuclear spin of $I=1$ is assumed for $\mathrm{Ne}^{20}$, we find that $\mu(\mathrm{Ne}^{20})\leq 4.1\times10^{-4}$ nuclear magneton, upon neglect of any possible electric quadrupole moment effect. Since no nucleus with nonzero spin is known with a nuclear magnetic moment less than $2\times10^{-3}$ nm,[10] this limit constitutes strong evidence that the spin of $\mathrm{Ne}^{20}$ is zero. An upper limit of $5\times10^{-2}$ nm for $\mathrm{Ne}^{20}$ had been previously determined by an atomic beam deflection measurement.[11]

## ACKNOWLEDGMENTS

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## APPENDIX

The notation and approach of Abragam and Van Vleck have been followed in evaluating the relativistic and diamagnetic corrections to the $g_J$ values for Ne and A in their ${}^3P_2$ states. The relativistic correction to $g_J$ for the $p^5$ configuration, which is proportional to the kinetic energy $\bar{T}$, is much larger than the diamagnetic corrections and it has been evaluated with two different wave functions. For one of the $p^5$ electrons with the use of Slater's rough analytic wave functions,[12] whose form is given below, we find

$$\bar{T}/m_0c^2=256\times10^{-6} \text{ for neon}$$

and

$$\bar{T}/m_0c^2=69.6\times10^{-6} \text{ for argon.}$$

With Hartree-Fock wave functions computed by Knox,[13] we obtain

$$\bar{T}/m_0c^2=256\times10^{-6} \text{ for neon}$$

and

$$\bar{T}/m_0c^2=170\times10^{-6} \text{ for argon.}$$

For neon the two wave functions give identical results but for argon the $\bar{T}$ from the Hartree-Fock wave function is almost twice as large as that from the Slater

[9] G. M. Grosof, P. Buck, W. Lichten, and I. I. Rabi, Phys. Rev. Letters **1**, 214 (1958).
[10] I. Lindgren, C. M. Johanssen, and S. Axensten, Phys. Rev. Letters **1**, 473 (1958).
[11] J. M. B. Kellogg and N. F. Ramsey, Phys. Rev. **53**, 331 (1938).
[12] J. C. Slater, Phys. Rev. **36**, 57 (1930).
[13] R. S. Knox, Phys. Rev. **110**, 375 (1958); A. Gold and R. S. Knox, Phys. Rev. **113**, 834 (1959).

wave function. A possible explanation of these results is the following. In neon the $2p$ electron wave function is always positive and has one maximum, so that the Slater wave function, which also is always positive and has one maximum, may be a reasonable approximation. For argon, however, the $3p$ electron wave function has one maximum and one minimum and hence $\psi^*\psi$ has two maxima and a node. It is not surprising, therefore, that the Slater wave function is a poor approximation for argon, and for this reason we believe that $\bar{T}$ evaluated using the Hartree-Fock wave function is more accurate. We thus use it for evaluating the $p^5$ contribution to the relativistic corrections.

The diamagnetic corrections and the $s$ electron relativistic correction have been evaluated using normalized Slater wave functions for each electron of the form

$$\psi=[(2b)^{2a+3}/\Gamma(2a+3)]^{\frac{1}{2}}r^a e^{-br}Y_l^m(\theta,\phi),$$

where $a=n^*-1$, $b=(Z-S)/n^*a_0$, and $n^*$ and $S$ are defined by Slater. The relativistic correction for a $p^5s$ configuration is

$$\Delta g=-\frac{4}{5}\left(\frac{\bar{T}}{m_0c^2}\right)_{p\text{ electron}}-\frac{1}{3}\left(\frac{\bar{T}}{m_0c^2}\right)_{s\text{ electron}},$$

and for a Slater wave function,

$$\frac{\bar{T}}{m_0c^2}=-\frac{\alpha^2}{2}\frac{(Z-S)^2}{n^*}\left\{\frac{2a}{2a+1}-1-\frac{2l(l+1)}{(a+1)(2a+1)}\right\}.$$

TABLE III. Contribution to $\bar{W}$ and $\bar{V}$ for neon and argon. The notation is that used by Abragam and Van Vleck.[a]

| Contributions to $\bar{V}$ or $\bar{W}$ from | Neon $\bar{W}\times10^6$ 2$p$ hole | $3s$ | $\bar{V}\times10^6$ 2$p$ hole | $3s$ |
|---|---|---|---|---|
| $(1s)^2$ | 0.08 | 0.00 | 0.35 | 0.00 |
| $(2s)^2(2p)^5$ | 3.38 | 0.00 | 1.64 | 0.105 |
| $3s$ | 0.23 | ... | 0.00 | ... |
| Total | 3.69 | 0.00 | 1.99 | 0.11 |

| Contributions to $\bar{V}$ or $\bar{W}$ from | Argon $\bar{W}\times10^6$ 2$p$ hole | $4s$ | $\bar{V}\times10^6$ 2$p$ hole | $4s$ |
|---|---|---|---|---|
| $(1s)^2$ | 0.00 | 0.00 | 0.017 | 0.00 |
| $(2s)^2(2p)^6$ | 0.11 | 0.00 | 0.832 | 0.00 |
| $(3s)^2(3p)^5$ | 1.83 | 0.00 | 0.967 | 0.087 |
| $4s$ | 1.46 | 0.00 | 0.00 | ... |
| Total | 3.40 | 0.00 | 1.816 | 0.087 |

[a] See reference 8.

The Lamb and orbit-orbit corrections, which are given in terms of $\bar{W}$ and $\bar{V}$, have been evaluated with an IBM 650 computer using Slater wave functions and are given in Table III. The forms of these corrections for a $p^5s$ configuration are

$$g_{\text{Lamb}}=-\frac{\alpha^2}{6}\left(\bar{W}-\frac{\bar{V}}{5}\right)_{p\text{ electron}}-\frac{\alpha^2}{6}\bar{W}_{s\text{ electron}},$$

$$g_{\text{orbit-orbit}}=-\frac{\alpha^2}{6}(\bar{V}+\bar{W})_{p\text{ electron}}.$$