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To cite this article: J R Persson 2018 *J. Phys. Commun.* **2** 055028

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Hyperfine structure and hyperfine anomaly in Pb

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Abstract

The hyperfine structure in the $6p^2$-configuration in lead has been analysed and the results are compared with calculations. The hyperfine anomaly and improved values of the nuclear magnetic moment for four lead isotopes are obtained, using the results from the analysis. Using the the trend recommended adjustment of the nuclear magnetic moment in four isotopes is suggested. The results open up for new measurements of the hyperfine structure in unstable lead isotopes, in order to obtain improved values of the nuclear magnetic moment, extract information of the hyperfine anomaly and distribution of magnetisation in the nucleus.

1. Introduction

Lead is an element of interest in both atomic and nuclear physics. With Z being a magic number and ^{208}Pb a doubly magic nucleus, lead is interesting from a nuclear physics view, with the possibility of systematic studies of nuclear properties. Using methods from atomic physics to study the hyperfine structure (hfs) and isotope shifts (IS), information on the nuclear moments and changes in nuclear charge radii can be obtained. The relatively simple atomic structure and the significant relativistic effects make lead suitable for testing different theoretical approaches and calculation methods. The present paper aim at showing how atomic data can be used to obtain additional information on the nucleus, namely the effect of the distribution of magnetisation in the nucleus, the Bohr-Weisskopf effect or hyperfine anomaly.

The hfs and IS in PbI have over the years been studied using different techniques. The electronic ground configuration of lead is $6p^2$, which gives rise to five low-lying, even-parity, metastable states: $^1S_0$, $^3P_{0,1,2}$, $^1D_2$. The first odd-parity state $(6p7s\ ^3P_0)$ has an energy of 34960 cm^{-1}, which places most transitions from the metastable states in the ultraviolet region. This made high-resolution laser spectroscopy difficult until the advent of frequency doubled cw lasers. The high-lying metastable $6p^2\ ^1D_2$ (21457.8 cm^{-1}) state is accessible through transitions in the IR. As we are interested in both the atomic and nuclear properties, a brief review of hfs measurements in both stable and unstable isotopes are given in section 2.

In order to use the experimental results in a deepened analysis, aimed at the hyperfine anomaly, a number of steps have to be taken. This includes an analysis of the eigenvectors, using both energy levels as well as experimental g_J factors in section 3.1. The hfs is analysed based on the effective operator formalism, using the obtained eigenvectors, and compared with published calculations in section 3.2. The method of obtaining the hyperfine anomaly is described in section 4 and applied, using the results in previous sections, on unstable isotopes in section 5. The state-independent hyperfine anomalies obtained are thereafter used to get better values for the nuclear magnetic moments in four isotopes and shows the need for corrections in four additional isotopes.

2. Experimental hyperfine structure constants

The hfs in Pb has been studied by different methods over the years, using optical spectroscopy as well as with the Atomic Beam Magnetic Resonance (ABMR) technique. With the advent of lasers, especially in the UV-region, more studies have been done. In table 1 an overview of the experimental hfs constants in ^{207}Pb for a number of

Table 1. Magnetic hyperfine structure constants A of the ^{207}Pb levels, in MHz.

Designation	A (ABMR)	A (corrected)	A (Laser)	A (Laser)
$6s^2\,6p^2\,^3P_1$	−2390.976 (2)[1]	−2390.881 (2)	−2389.4 (7)[2]	−2388.2 (4.5)[3]
$6s^2\,6p^2\,^3P_2$	2602.060 (1)[1]	2602.144 (1)	2600.8 (9)[2]	
$6s^2\,6p^2\,^1D_2$	609.818 (8)[4]	609.818 (8)		
$6s^2\,6p7s\,^3P_1$			8802.0 (1.6)[2]	8807.2 (3.0)[5]

Table 2. Magnetic hyperfine structure constants A and B of the unstable isotopes in lead, in MHz.

Isotope	I	A ($6p^2\,^1D_2$)	B ($6p^2\,^1D_2$)	A ($6p7s\,^3P_1$)	B ($6p7s\,^3P_1$)	References
^{183}Pb	3/2			−5742(25)	70(200)	[7]
^{183m}Pb	13/2			−1423(6)	−200(400)	[7]
^{185}Pb	3/2			−5652(25)	−30(150)	[7]
^{185m}Pb	13/2			−1405(12)	−110(150)	[7]
^{187}Pb	3/2			−5580(10)	50(200)	[7]
^{187m}Pb	13/2			−1383(5)	60(300)	[7]
^{189}Pb	3/2			−5360(40)	−60(200)	[7]
^{189m}Pb	13/2			−1360(10)	150(40)	[7]
^{191}Pb	13/2	−91.3(6)	123(18)	−1344(1)	−15(8)	[6]
^{193}Pb	13/2	−89.6(5)	282(14)	−1321(1)	−19(7)	[6]
^{195}Pb	13/2	−88.1(6)	442(19)	−1294(1)	−33(9)	[6]
^{197}Pb	3/2			−5327(11)	9(20)	[5]
^{197m}Pb	13/2	−85.7(9)	546(23)	−1261(7)	−59(12)	[6]
				−1263(3)	−54(39)	[5]
^{199}Pb	3/2			−5322(6)	−9(10)	[5]
^{201}Pb	5/2			2007.5(1.3)	1(5)	[5]
^{202m}Pb	9			−187.9(5)	−67(9)	[5]
^{203}Pb	5/2			2040.3(1.3)	−11(6)	[5]
^{205}Pb	5/2			2115.7(8.0)	−26(4)	[5]
^{209}Pb	9/2			−2433(3)	31(19)	[5]
^{211}Pb	9/2			−2318.3(1.3)	10(13)	[5]

states of interest are given. The hfs constants from high accuracy measurements have been corrected with respect to the non-diagonal hyperfine interaction.

There also exist studies of the hfs in unstable isotopes [5–7]. A compilation of the hfs constants obtained is given in table 2. These studies have mainly been concerned with the IS, i.e. the change in nuclear charge radii, hence the use of states without hfs.

As can be seen, the hfs is known in only one state for most isotopes, with the exception of four isotopes. As we are interested in the hyperfine anomaly these isotopes will be studied in detail.

3. Analysis of the hyperfine structure

3.1. Eigenvectors

Lead has a quite simple ground electronic configuration, but deviates from pure LS-coupling, in fact, it is close to pure jj-coupling. Still, it is possible to use LS-coupling basis in the analysis. In order to perform an analysis of the hfs, the breakdown of LS-coupling must be taken into account and eigenvectors have to be obtained.

The eigenvectors can be obtained by diagonalising the energy matrix of the spin-orbital and the electrostatic interactions or by an analysis of the experimental g_J factors. The energy matrix has been derived by, for example, Condon and Shortley [8]. The agreement between the fitted and experimental energy levels using this energy matrix is not particularly good. Landman and Lurio [4] included spin-spin, orbit-orbit and spin-other-orbit interactions but this did not improve the fit.

Instead of using the energy matrix, an analysis of the experimental g_J factors will probably give a better description of the system. The experimental g_J factors can be described as:

$$g_J^{\text{exp}} = \alpha^2 g_J^{LS}(LS) + \beta^2 g_J^{LS}(L'S') \tag{1}$$

where g_J^{LS} is the Lande g_J factor for a pure LS-state corrected for the anomalous spin of the electron, α and β are the intermediate coupling coefficients.

Table 3. Experimental g_J factors compared with values corrected for relativistic and diamagnetic effects.

State	Lande value	Corrections [10]	Calculated	Experimental [1, 4]
$^3P_1$	1.5011596	−0.0001060	1.5010536	1.500755(10)
$^1D_2 + {}^3P_2$	2.5011596	−0.0002783	2.5008813	2.50148(11)

Table 4. Obtained eigenvectors.

	α	β
Case A	0.765717	0.643178
Case B	0.7636	0.6457
Case C	0.740780(23)	0.671748(158)

Table 5. Values of the effective radial parameters in MHz.

	a^{01}	a^{12}	a^{10}
Case A	2365.68	5395.26	−1752.18
Case B	2377.74	5375.16	−1784.34
Case C	2518.80(88)	5134.10(88)	−2158.01(12)

The experimental g_J factors must be corrected for diamagnetic and relativistic effects [9, 10]. In lead, these corrections are of the order $5 \cdot 10^{-4}$, as can be seen when comparing the experimental g_J factor for the $^3P_1$ state with the corrected g_J factor in table 3. A Hartree–Fock calculation of these diamagnetic and relativistic corrections has been done in [10] and the result is presented in table 3. In order to exclude coupling effects, the sum of the g_J factor for the J = 2 states are given.

The calculated corrections were not as large as expected, why configuration interaction effects should be important. It has been shown by Gil and Heldt [11] that there exists a configuration mixing between the $6p^2$ and $6p7p$ configurations, by including configuration interactions in the energy matrix analysis. Even though their fit suffers from the same problems as in the ordinary matrix analysis, a calculation of the g_J factors using their eigenvectors and including diamagnetic and relativistic corrections gave an excellent agreement in comparison with experimental data [10].

In this case, we exclude the configuration interaction when analysing the g_J factors, and as a precaution, in order to obtain accurate eigenvectors, the estimated errors of the relativistic and diamagnetic corrections were enlarged.

All obtained eigenvectors are given in table 4. In case A the eigenvectors are obtained by analysing the energy levels according to the energy matrix of Condon and Shortley [8], in case B eigenvectors are derived by Landman and Lurio [4] and in case C the eigenvectors are obtained by analysing the experimental g_J factors.

3.2. Hyperfine interaction

The analysis of the hyperfine interaction is based on an effective hyperfine hamiltonian, which for the magnetic dipole interaction is written as [12]:

$$H^1_{hfs,eff} = 2\frac{\mu_0}{4\pi}\mu_B \sum_{i=1}^{N}\left[\mathbf{l}_i \cdot \langle r^{-3}\rangle^{01} - \sqrt{10}\frac{g_s}{2}(\mathbf{sC}^2)^1_i \cdot \langle r^{-3}\rangle^{12} + \frac{g_s}{2}\mathbf{s}_i \cdot \langle r^{-3}\rangle^{10}\right]\cdot\mathbf{M}^1 \tag{2}$$

By determination of the angular parts, using the eigenvectors, the magnetic dipole interaction constants 'A' can be expressed as a linear combination of the orbital (01), spin-dipole (12), and contact (10) effective radial parameters (a^{ij}).

$$A = k^{01}a^{01} + k^{12}a^{12} + k^{10}a^{10} \tag{3}$$

The numbers in the parentheses correspond to the rank of the spherical tensor operators in the spin and orbital spaces. In this way can the effective radial parameters for the different eigenvectors be fitted to the corrected A factors.

The obtained effective radial parameters are presented in table 5. The errors in the effective radial parameters are mainly due to the uncertainty of the eigenvectors since the errors in the energy fit are quite large and hard to obtain, these errors are expected to be on the order of 10%. In the analysis of the experimental g_J factors, the errors are possible to obtain.

Table 6. Experimental and calculated hyperfine integrals (in units of a_0^{-3}).

	$\langle r^{-3}\rangle^{01}$	$\langle r^{-3}\rangle^{12}$	$\langle r^{-3}\rangle^{10}$
HF [12]	22.302	44.390	−7.337
OHFS [12]	22.898	48.076	−8.519
Exp case A	20.921	47.713	−15.495
Exp case B	21.028	47.535	−15.780
Exp case C	22.2750(84)	45.4034(86)	−19.0844(15)

The effective radial parameters, proportional to the nuclear moment and the effective $\langle r^{-3}\rangle$ values can be expressed as [12]:

$$a^{ij} = 2\frac{\mu_0}{4\pi}\mu_B\frac{\mu_I}{I}\langle r^{-3}\rangle^{ij} \tag{4}$$

Since the nuclear magnetic dipole moment has been determined independently ($\mu_I = +0.592583(9)$ n.m.), it is possible to derive the effective $\langle r^{-3}\rangle$ values. These semi-empirical values are presented in table 6 together with calculated $\langle r^{-3}\rangle$ values from Lindgren and Rosen [12], using the relativistic Hartree–Fock (HF) and Optimized Hartree–Fock-Slater (OHFS) methods. The values for HF should be similar to Dirac-Fock not including Breit terms OHFS represents a Slater type potential with some optimised parameters as discussed in [12].

The calculated relativistic values of $\langle r^{-3}\rangle^{01}$ differ from the experimental value (case C) by 1.4% for the OHFS and 1.3%, for the HF method, while the corresponding difference between the calculated and experimental values of $\langle r^{-3}\rangle^{12}$ is 4.4% and 3.7%, respectively. The large difference between the experimental and calculated values of $\langle r^{-3}\rangle^{10}$ are due to spin and core polarisation. Bouazza *et al* [2] estimated the fraction of the spin polarisation to be 50.62%, as shown in the isoelectronic Bi II [13]. Using this we get a value of $\langle r^{-3}\rangle^{10} = -16.06 a_0^{-3}$, in reasonable agreement with the experimental values.

4. Hyperfine anomaly

In addition to the hyperfine interaction and nuclear magnetic dipole moment is it possible to obtain information on the distribution of magnetisation in the nucleus through the so-called Bohr-Weisskopf effect (BW-effect) [14–16]. The first to consider the influence of the finite size of the nucleus on the hyperfine structure was Bohr and Weisskopf [14]. They calculated the hyperfine interaction of $s_{1/2}$ and $p_{1/2}$ electrons for an extended nucleus, and showed that the magnetic dipole hyperfine interaction constant (A) for an extended nucleus is generally smaller than for a point nucleus. The effect on the hyperfine interaction from the extended charge distribution of the nucleus gives rise to the so-called Breit-Rosenthal effect (BR-effect) [17–20]. In this case, as in most but not all cases, the differential BR-effect is negligible when two isotopes are compared. Inclusion of the BR-effect will not have any effect on the results, since the BW- and BR-effects show the same behaviour. The BR-effect is therefore excluded in the following discussion. Isotopic variations of magnetic moments became larger than those in the point dipole interaction since there are different contributions to the hfs from the orbital and spin parts of the magnetisation in the case of extended nuclei. The fractional difference between the point nucleus hfi constant (A_{point}) and the constant obtained for the extended nuclear magnetisation is commonly referred to as the Bohr-Weisskopf (BW) effect [16]. The hfs constant A can therefore be written as

$$A = A_{point}(1 + \epsilon_{BW}) \tag{5}$$

where ϵ_{BW} is the BW-effect, and A_{point} is the A constant for a point nucleus. The BW-effect is dependent on both nuclear and atomic properties, i.e. the electron density within the nucleus. The nuclear part, i.e. the distribution of nuclear magnetisation, can be calculated using different nuclear models [15, 16]. Since electronic wavefunctions cannot be calculated with sufficient high accuracy in complex atoms, as they can be in hydrogen-like ions and muonic atoms, it is not possible to determine ϵ_{BW} directly in atoms. However, it is possible to determine the difference of the BW-effect in two isotopes, the so-called (differential) hyperfine anomaly (hfa). Comparing the ratio of the measured hfs constants for two isotopes with the independently measured ratio of the nuclear magnetic dipole moments to extract the hfa,$^1\Delta^2$, for the isotopes 1 and 2, and a given atomic state, gives:

$$1 +^1\Delta^2 = \frac{A^{(1)}}{A^{(2)}}\frac{\mu_I^{(2)}/I^{(2)}}{\mu_I^{(1)}/I^{(1)}} \approx 1 + \epsilon_{BW}^{(1)} - \epsilon_{BW}^{(2)} \tag{6}$$

where μ_I is the nuclear magnetic dipole moment, and I the nuclear spin. In the case of electrons with a total angular momentum j > 1/2, the anomalies may be disregarded as the corresponding wavefunctions vanish at the nucleus. The hfa can show a dependence of the atomic state, a state-dependent hfa, where the values for different states can vary significantly [16]. The reason for the state dependence is that the hyperfine interaction consists of three parts [21, 22], orbital, spin-orbit and contact (spin) interaction, where only the contact interaction contributes to the hfa. Since the contribution of the different interactions differs between different atomic states, and it is only the spin interaction giving rise to the hfa, a state-dependent hfa is the result. It is therefore suitable to rewrite the dipole hyperfine interaction constant as

$$A = A_{nc} + A_c \tag{7}$$

where A_c is the contribution due to the contact interaction of s (and $p_{1/2}$) electrons and A_{nc} is the contribution due to non-contact interactions. The experimental hfa, which is defined with the total magnetic dipole hyperfine constant A, should then be rewritten to obtain the relative contact contribution to the hfa:

$$^1\Delta^2_{exp} =^1 \Delta^2_c \frac{A_c}{A} \tag{8}$$

where $^1\Delta^2_c$ is the hfa due to the contact interaction, that is, for an s- or $p_{1/2}$-electron.

From the discussion, one might come to the conclusion that one needs independent measurements of the nuclear magnetic moments and the A-constants in order to obtain the hfa, however, this is not true. As has been shown by Persson [23], it is possible to extract the anomaly solely from the A-constants of two different atomic states, provided the ratio $\left(\frac{A_c}{A}\right)$ differs for the different states. Comparing the A-constant ratio, for two isotopes, in two atomic states, gives:

$$\frac{A_B^{(1)}/A_B^{(2)}}{A_C^{(1)}/A_C^{(2)}} \approx 1 +^1 \Delta^2_c \left(\frac{A_c^B}{A^B} - \frac{A_c^C}{A^C}\right) \tag{9}$$

Where B and C denote different atomic states and 1 and 2 denote different isotopes. The ratio between the two A-constant ratios for the isotopes will therefore only depend on the difference in the contact contributions of the two atomic states and the hfa. It should also be noted that the ratio $\left(\frac{A_c}{A}\right)$ is isotope independent. Once determined for one isotopic pair, the ratio can be used for all pairs, which is very useful in the study of hfa in radioactive isotopes. It is possible to determine the ratio in two different ways; either by an analysis of the hyperfine interaction or by using a known hfa as a calibration. It should be noted that the atomic states used must differ significantly in the ratio $\left(\frac{A_c}{A}\right)$, as a small difference will lead to an increased sensitivity to errors.

Since the hfa is normally very small (1% or less) it is often necessary to have high accuracy for the A-constants, preferably better than 10^{-4} [16]. In stable isotopes, there is no major problem to measure the nuclear magnetic moment with sufficient accuracy using NMR or ABMR, while for unstable isotopes it is more difficult. In most cases, there does not exist any high precision measurements of the nuclear magnetic moment and the nuclear magnetic moment is deduced from the hfs while neglecting the effect of hfa. However, there might exist measurements of two A-constants, if the nuclear charge radius of the unstable isotopes has been measured by means of laser spectroscopy. In order to obtain the hfa one, therefore, needs to measure the A-constants with an accuracy better than 10^{-4}, something that can be done by laser spectroscopy provided the A-constant is larger than about 1000 MHz, as is the case in Pb.

5. Hyperfine anomaly in unstable isotopes

From table 2 we see that the A constants are known for two states in four unstable isotopes, ^{191}Pb, ^{193}Pb, ^{195}Pb and ^{197m}Pb. The complication is that one state has a small A constant and the other belongs to the $6p7s$ configuration. Still, it is possible to obtain a state-dependent hyperfine anomaly using:

$$\frac{A_B^{(1)}/A_B^{(2)}}{A_C^{(1)}/A_C^{(2)}} \approx 1 +^1 \Delta^2_{exp} \tag{10}$$

with the A constants from ^{207}Pb, as reference nucleus (1). The state dependent hyperfine anomalies obtained are given in table 7.

Note that the hfa contains contributions from both states involved. This makes the contact contribution of the hyperfine interaction is quite complicated with both s and $p_{1/2}$ electrons. However, it is possible to examine the hyperfine interaction in the $6p7s\,^3P_1$ further. Bouazza *et al* [2] give the eigenvector components for this state, and by assuming that the effective hyperfine interaction parameters for the p electrons are the same in the $6p^2$ and $6p7s$ configurations, we can deduce a value of the s electron effective hyperfine interaction parameter.

Using the eigenvector we find that the A constant for the $6p7s\,^3P_1$ in ^{207}Pb can be expressed in effective hyperfine interaction parameters as:

Table 7. State-dependent (exp) and state-independent (c) hyperfine anomaly in unstable Pb isotopes.

Isotope	$^{207}\Delta^A_{\mathrm{exp}}$ (%)	$^{207}\Delta^A_c$ (%)
^{191}Pb	−1.94(68)	−1.72(68)
^{193}Pb	−2.10(58)	−1.86(58)
^{195}Pb	−1.73(70)	−1.53(70)
^{197m}Pb	−1.90(123)	−1.68(123)

Table 8. Nuclear magnetic dipole moments from [6] and derived correcting for the hyperfine anomaly. The errors are only from experimental uncertainty.

Isotope	$\mu_I(^1D_2)$	$\mu_I(^1D_2)$ [6]	$\mu_I(^3P_1)$	$\mu_I(^3P_1)$ [6]	μ_I(mean, this work)
^{191}Pb	−1.167(15)	−1.155(15)	−1.168(8)	−1.176(8)	−1.168(8)
^{193}Pb	−1.147(14)	−1.133(14)	−1.147(8)	−1.156(8)	-1.147(7)
^{195}Pb	−1.125(15)	−1.114(15)	−1.125(8)	−1.132(8)	-1.125(7)
^{197m}Pb	−1.095(19)	−1.084(19)	−1.094(14)	−1.103(14)	−1.094(13)

$$A(6p7s\,^3P_1) = 0.63815a_p^{01} + 0.67804a_p^{12} - 0.13526a_p^{10} + 0.49712a_s^{10} \tag{11a}$$

$$= 8802.0(1.6)\,\mathrm{MHz} \tag{11b}$$

Using the effective hyperfine interaction parameters for the p electrons in table 5, gives the s electron parameter $a_s^{10} = 6884$ MHz, which is a reasonable value. It is now possible to calculate the contact contribution in equation (9), both for the $6p7s\,^3P_1$ and $6p^2\,^1D_2$ states.

$$\frac{A_c}{A}(6p7s\,^3P_1) = 0.422 \tag{12}$$

$$\frac{A_c}{A}(6p^{21}D_2) = -0.708 \tag{13}$$

Using this it is possible to obtain the state independent contact anomaly. It must be noted that the contact anomaly consists of both s- and $p_{1/2}$-electron parts. If we assume that the contribution to the hyperfine anomaly is the same for s- and p- electrons we must correct the obtained state dependent hyperfine anomalies, using equation (9), by a factor 1.13 $(\frac{A_c}{A}(6p7s\,^3P_1) - \frac{A_c}{A}(6p^{21}D_2))$, giving the state independent hyperfine anomaly in table 7.

In order to check if the result is reasonable we can use the obtained hyperfine anomaly to calculate the nuclear magnetic dipole moment of the four isotopes using the measured A constants:

$$\frac{A^{(1)}}{A^{(2)}}\frac{\mu_I^{(2)}/I^{(2)}}{\mu_I^{(1)}/I^{(1)}} = 1 + {}^1\Delta_c^2\frac{A_c}{A} \tag{14}$$

rearranging gives

$$\mu_I^{(2)} = \frac{A^{(2)}}{A^{(1)}}\frac{I^{(2)}}{I^{(1)}}\mu_I^{(1)}\left(1 + {}^1\Delta_c^2\frac{A_c}{A}\right) \tag{15}$$

Using this we can calculate the nuclear magnetic dipole moment for both atomic states, the results are given in table 8.

The agreement between the different states is much better for the corrected values, giving a better value for the nuclear magnetic moments.

Assuming that the hyperfine anomaly is fairly constant for all 13/2-isotopes (1.7(1.0)%) as has been found in Hg [24], it is possible to correct the nuclear magnetic moment for the 13/2 isotopes measured with only one A-factor [7]. The corrected values are given in table 9.

6. Discussion

The hyperfine structure of ^{207}Pb has been analysed and the analysis has been used as the basis for determining the hyperfine anomaly in four unstable isotopes, $^{191}Pb, ^{193}Pb, ^{195}Pb$ and ^{197m}Pb, using the method of Persson [23]. The derived hyperfine anomaly has then been used to obtain better values of the nuclear magnetic moment for these isotopes. There exist measurements in other unstable isotopes, table 2, but only in one state that exhibits hyperfine structure, why it is not possible to derive the hyperfine anomaly or correct the nuclear magnetic

Table 9. Nuclear magnetic dipole moments from [7] and values corrected for the hyperfine anomaly. The errors in brackets is from experimental uncertainty and uncertainty in the hyperfine anomaly, respectively.

Isotope	$\mu_I(^3P_1)$ [7]	$\mu_I(^3P_1)$ corrected
^{183}Pb	−1.245(6)	−1.237(6)(4)
^{185}Pb	−1.23(1)	−1.221(10)(4)
^{187}Pb	−1.210(5)	−1.202(5)(4)
^{189}Pb	−1.19(1)	−1.182(10)(4)

moments in these isotopes. Assuming that the hfa is fairly constant for nuclei with the same nuclear spin, a correction of the nuclear magnetic moment due to hfa can be obtained, as has been done in four isotopes. It would be possible to obtain both hfa and corrections if another atomic state is measured in these isotopes, preferably the $6p^2\,^1D_2$. It is also possible to make the new measurements in the $6p^2\,^3P_1$ or $^3P_2$, as the hfs is larger in these states than the $^1D_2$ state. The optimum would be to make measurements in all possible states in the $6p^2$ configuration, thus giving in total three atomic states that enable a cross-check of the results. The $^3P_1$ state offer another complication, as the contact contribution to the hyperfine structure in this state ($\frac{A_c}{A} = 0.452$) is close to the contribution of the $6p7s\,^3P_1$ state ($\frac{A_c}{A} = 0.422$), which is not suitable for an analysis of the hyperfine anomaly [23]. The contact contribution to the hyperfine structure for the $6p^2\,^3P_2$ state ($\frac{A_c}{A} = -0.247$), is suitable for analysis with all other states. An experiment where the hyperfine structure of the $6p^2\,^3P_2$ state in unstable isotopes of lead are measured would give both better values of the nuclear magnetic moments as well as values of the hyperfine anomaly.

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