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THE SPIN POLARISABILITY OF THE ELECTRON.

by
M. W. Evans,
Theory Center,
Cornell University,
Ithaca,
NY 14850.

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Abstract

The concept is introduced of electron spin polarisability, a new fundamental property of the electron which has no classical counterpart and whose existence can be tested experimentally by a theoretically predicted laser induced analogue of the anomalous Zeeman effect and electron spin resonance. Conditions are suggested for the experimental investigation, using the conjugate product of a Nd:YAG pump laser in a modified NMR/ESR spectrometer.

It is well known that the electron has a quantised spin angular momentum, which is a fundamental property of matter and which has no classical analogue. The electronic spin is responsible for electron paramagnetic (or spin) resonance (EPR or ESR) and for spectral splittings such as those induced in the anomalous Zeeman effect (1) by static magnetic flux density (B). In this letter we introduce an analogous but novel fundamental property of the electron, which is called its "spin polarisability" $\underset{\sim}{\alpha}''_S$. The existence of this property is argued for theoretically using symmetry, and a suggestion is made for its experimental investigation using a laser induced analogue of the anomalous Zeeman effect and electron spin resonance.

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The relevant laser property is the conjugate product, $\underset{\sim}{\pi}$, which is proportional (2,3) to the third Stokes parameter and which is isolated using a pump laser such as a Nd:YAG, a quarter wave plate and Nicol prism (4). The conjugate product is

$$\underset{\sim}{\pi} = \underset{\sim}{E}_L^+ \times \underset{\sim}{E}_L^- = - \underset{\sim}{E}_R^+ \times \underset{\sim}{E}_R^- = 2E_o^2 i \underset{\sim}{k} \quad - (1)$$

where $\underset{\sim}{E}$ is the electric field strength in volts m^{-1}, and where the subscripts L and R denote respectively left and right circularly polarised. The superscripts + and - denote plus and minus conjugates (4-6) of the electromagnetic plane wave from Maxwell's equations. Here k is a unit vector in the Z axis of the laboratory frame. The conjugate product is negative to motion reversal (T) and positive to parity inversion (P) and changes sign from left to right circular polarisation.

It has been shown (7-9) that the interaction hamiltonian of $\underset{\sim}{\pi}$ with atomic or molecular ensembles is

$$\Delta H_1 = - \frac{1}{2} \alpha_i \pi_i = \frac{i}{2} \left(\underset{\sim}{\alpha}''_{oi} + \underset{\sim}{\alpha}''_{si} \right) \pi_i \quad - (2)$$

where $\underset{\sim}{\alpha}''_{oi}$ is a new fundamental property called the electronic orbital polarisability. The latter is a T negative, P positive axial vector (i.e. a rank two antisymmetric polar tensor) which is proportional to the total atomic or molecular angular momentum

$$\underset{\sim}{J} = \underset{\sim}{L} + 2.002 \underset{\sim}{S} = \gamma_\pi^{-1} \left(\underset{\sim}{\alpha}''_o + \underset{\sim}{\alpha}''_s \right) \quad - (3)$$

where γ_π is a proportionality constant analogous to the well known gyromagnetic ratio between $\underset{\sim}{J}$ and $\underset{\sim}{B}$ used in the theory of electron spin resonance. It has been shown (9) that

$$\gamma_\pi \propto \frac{\gamma_e}{E_o c} \quad - (4)$$

where E_o is the scalar amplitude of the electric field strength of the laser, c the velocity of light, and γ_e the gyromagnetic ratio.

In general the angular momentum $\underset{\sim}{J}$ is a composite of orbital and spin components. For the electron, it can be written as

$$\underset{\sim}{J} = \underset{\sim}{L} + 2.002\,\underset{\sim}{S} \qquad -(5)$$

where $\underset{\sim}{L}$ is the quantised electronic orbital and $2\underset{\sim}{S}$ the electronic spin angular momentum, the factor 2 being derived essentially from the relativistic treatment by Dirac of quantum mechanics. It follows from eqns (3) and (5) that the quantity $\underset{\sim}{\alpha''}$ has both an orbital and spin component, the latter being a new fundamental property of the electron which is named here the "spin polarisability", and which has no classical counterpart.

Its existence can be investigated experimentally by using the electron spin resonance or anomalous Zeeman effect generated by the hamiltonian (2). In both cases the conjugate product π_i plays the role customarily attributed to B. The pump laser generates π_i using the following configuration (4) of quarter wave plate and Nicol prism

$$S_3 \propto I\left(\frac{3\pi}{4}, \frac{\pi}{2}\right) - I\left(\frac{\pi}{4}, \frac{\pi}{2}\right) \qquad -(6)$$

Here $I(\sigma, \tau)$ denotes the intensity of pump laser radiation transmitted through a retarder (the quarter wave plate) which subjects its Y component to a retardation τ with respect to its X component, followed by an analyzer with its transmission axis oriented at an angle σ to the X axis. Thus $I(\sigma, \tau)$ is the excess in intensity transmitted by a device which accepts left circularly polarised radiation over that transmitted by a device which accepts right circularly polarised electromagnetic radiation. Note that this is the definition of the intensity

corresponding (10) to the third Stokes parameter S_3 , which is proportional to the conjugate product $\underset{\sim}{\pi}$ through

$$\underset{\sim}{\pi} = -i S_3 \underset{\sim}{k} \qquad -(7)$$

The conjugate product obtained in this way from a small, inexpensive, and commercially available Nd:YAG pump laser generates spectral effects customarily attributed to $\underset{\sim}{B}$, which has the same negative T and positive P symmetries. Two examples relevant to the new property of electron spin polarisability are : 1) laser induced anomalous Zeeman effect; and 2) laser induced electron spin resonance.

1) Pump Laser Induced Anomalous Zeeman Effect

The Zeeman effect is customarily generated by $\underset{\sim}{B}$, and is the splitting of spectral absorption lines (11). The anomalous Zeeman effect is due to a combination of the effects of $\underset{\sim}{B}$ on electron orbital and spin angular momentum through the hamiltonian

$$\Delta H_2 = -\gamma_e \left(\underset{\sim}{L} + 2.002 \underset{\sim}{S} \right) \cdot \underset{\sim}{B} \qquad -(8)$$

An analogous effect can be generated through the hamiltonian

$$\Delta H_3 = -\gamma_\pi \left(\underset{\sim}{L} + 2.002 S \right) E_o^2 \qquad -(9)$$

due to the pump laser induced optical conjugate product $\underset{\sim}{\pi}$. The quantity $\gamma_\pi \underset{\sim}{L}$ is the "electronic orbital polarisability", and the other is the "electronic spin polarisability". The hamiltonian (9) can be re-written in terms of the Landé factor

$$\Delta H_3 = -\gamma_\pi g_J J_z E_o^2 \qquad -(10)$$

$$g_J = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)} \quad -(11)$$

ere

$$\underset{\sim}{J} = \underset{\sim}{L} + 2.002\,\underset{\sim}{S} \quad -(12)$$

the total electronic angular momentum, of magnitude $(J(J+1))^{1/2}\hbar$.

It is clear from (10) that when $S \neq 0$, the Landé factor pends both on L and S, and the laser conjugate product will lit different terms in different degrees. For example, a one he atomic transition $^2P_{1/2}$ to $^2D_{3/2}$ will be split into three ublets by the conjugate product $\underset{\sim}{\pi}$, governed by the lection rule

$$\Delta M_J = 0, \pm 1 \quad -(13)$$

the Z component quantum number of $\underset{\sim}{J}$.

Observation of these six lines would confirm the istence of new fundamental properties, the electronic spin and bital polarisabilities mediating the effect of $\underset{\sim}{\pi}$ on the omic vapour under investigation. The approximate frequency acing of the doublets is given by

$$\Delta\omega \doteq \alpha''_i E_0^2 / \hbar \quad -(14)$$

radians s^{-1}. For an order of magnitude estimate for the al electronic polarisability axial vector of $10^{-38} J^{-1} C^2 m^2$ s is

$$\Delta\omega \doteq 10^{-4} E_0^2 \text{ rad } s^{-1} \quad -(15)$$

terms of the square of the electric field strength of the pump er in volts m^{-1}. A small Q-switched and focussed Nd:YAG laser deliver (12) up to 10^9 volt m^{-1} in ultra short pulses of at power, so that the splitting is in the GHz range of the onating probe of customary ESR spectrometers for E_0 of about

10^6 volt m^{-1}. The magnitude of the polarisability α''_i can be increased greatly by tuning the pump frequency to a natural transition frequency of the atomic vapour, allowing the use of a much lower pump laser electric field strength.

2) Pump Laser Induced Electron Spin Resonance.

This technique is similar in principle to the anomalous Zeeman splittings due to $\underset{\sim}{\pi}$. The GHz splitting just discussed is made to resonate with probe electromagnetic radiation in the GHz range, as for example in a customary ESR spectrometer designed for use with $\underset{\sim}{B}$ of a homogeneous magnet. In general, the resonance condition is

$$\hbar\omega_R = E(1/2) - E(-1/2) = -2.002\,\gamma_\pi \pi_z \qquad (16)$$

which depends directly on the existence of the electron spin polarisability, whose Z axis component is $-2\gamma_\pi \pi_z \hbar M_s$ with a spin quantum number M_s taking values 1/2 and -1/2. The resonance frequency depends on the quantity γ_π defined through the proportionality in eqn. (4). The proportionality constant must be determined experimentally.

Finally it is clear that the conjugate product $\underset{\sim}{\pi}$ will also split a conventional nuclear magnetic resonance (NMR) line through the hamiltonian

$$\Delta H_4 = -\gamma_N \underset{\sim}{I} \cdot \underset{\sim}{B} - \gamma_\pi J_z E_0^2 \qquad (17)$$

where I is the nuclear spin quantum number and γ_N the nuclear gyromagnetic ratio. This can be re-written in the form

$$\Delta H_4 = -\gamma_N \left\{ 1 + \frac{I(I+1) - J(J+1)}{2J_T(J_T+1)} \right\} \underset{\sim}{J}_T \cdot \underset{\sim}{B}$$

$$- \gamma_\pi \left\{ 1 - \frac{I(I+1) - J(J+1)}{2J_T(J_T+1)} \right\} J_{TZ} E_0^2 \qquad (18)$$

where

$$J_T = I + J \qquad -(19)$$

s the total angular momentum quantum number. For $I \neq 0$, the ustomary NMR line, defined through the selection rule

$$\Delta M_I = \pm 1 \qquad -(20)$$

s split into a new pattern of lines dependent on the selection ule

$$\Delta M_{J_T} = 0, \pm 1 \qquad -(21)$$

nd on the individual values of I and J . This has vast otential application in the analytical laboratory, because odifications to include $\underline{\pi}$ can be made in standard NMR nstruments, including two-D and Fourier transform NMR, and NMR maging for different nuclei, pump laser frequencies, and lectric field strengths.

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