Linear Stark effect in atoms and mesic atoms in the presence of neutral weak currents

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It is shown that in the presence of weak neutral currents a splitting of the Stark levels of the atoms takes place with respect to the sign of the projection of the total angular momentum. The resultant splitting is calculated.

A splitting of levels having different absolute values of the projections M of the total angular momentum takes place for atoms in the ground state in a constant electric field (the Stark effect), but a degeneracy with respect to the sign of M still remains. This degeneracy is the consequence of T-invariance, by virtue of which the particles cannot have a dipole moment $\mathbf{d}$. For unstable particles, however, the presence of a width imitates violation of T-invariance, which in conjunction with the violation of space parity leads to the appearance of a dipole moment for such particles and atoms.[1] The resultant linear Stark effect leads to a splitting of levels with different signs of the projection M, in view of the proportionality $\mathbf{d} \sim \mathbf{J}$, where $\mathbf{J}$ is the total angular momentum of the atom. This splitting is equal to (the field F is assumed directed along the z axis)

$$\Delta E = 2 < d_z > F . \tag{1}$$

A favorable situation arises for the excited $2s_{1/2}$ level of the hydrogen atom and of isoelectronic ions, by virtue of the proximity of the $2p_{1/2}$ level, which has opposite parity. We consider for simplicity atoms whose nuclei have zero spin. The average value of the dipole moment for the state $2s_{1/2}$ is calculated with the wave function $\phi_{2s} + i\delta(\Gamma)\phi_{2p}$, where $\delta(\Gamma)$ is the coefficient of admixture due to the weak interaction G with allowance for the imaginary parts resulting from the instability. The quantity $\delta(0)$ without allowance for the instability is real and was calculated in[2]:

$$\delta(0) = -\frac{1}{32\pi}\sqrt{\frac{3}{2}}\, G m^2 (\alpha Z)^4 L^{-1} Q(ZN) = -1.2\cdot 10^{-11} Q(ZN) \tag{2}$$

where $L = E_s - E_p$ is the Lamb splitting, $E_{s,p}$ are the level energies, m is the electron mass, α is the fine-structure constant, $\hbar = c = 1$, Z is the charge of the nucleus, and $Q(ZN)$ is a coefficient that determines the dependence of the electron-nuclear neutral currents on the number of protons Z and the number of neutrons N in the nucleus. In the Weinberg model we have $Q(ZN) = -[0.4Z + N]/2$. For $\delta(\Gamma)$ we have the relation

$$\delta(\Gamma) = \delta(0)\frac{1}{1 + i\dfrac{\Gamma}{L}}, \tag{3}$$

where $\Gamma = \Gamma_s + \Gamma_p$, and $\Gamma_{s,p}$ are the total level widths. The dipole moment of the atom is

$$< d_z > = 2\mathrm{Re}\, i\,\delta(\Gamma) < \phi_{2s} \mid ez \mid \phi_{2p} > , \tag{4}$$

where $e = \sqrt{\alpha}$ is the electron charge. Calculating the matrix element $\langle \phi_{2s} | ez | \phi_{2p}\rangle = 2\sqrt{3}\, Mea$ ($a = 1/m\alpha Z = a_0/Z$, a_0 is the Born radius) and substituting (3) we obtain ($M = 1/2$):

$$\langle d_z \rangle = \sqrt{3}\delta(0)\frac{\Gamma}{L}\ ea = 2.1\cdot 10^{-12} Q(ZN)\frac{1}{Z}\ ea_0 = 1.1\cdot 10^{-20}\frac{Q}{Z}\text{cm}\,M. \tag{5}$$

Expression (5) is valid for weak fields, when the usual Stark splitting $S=2\sqrt{3}\ eaF$ is smaller than the Lamb shift L. The splitting, according to (1) and (5), is equal to

$$\Delta E = \delta(0)\,\xi\,\Gamma = 1{,}2\cdot 10^{-3}\,\xi Q(ZN)Z^4\,\text{Hz}, \tag{6}$$

where $\xi=F/F_0=S/L$, $F_0=L/2\sqrt{3}\,la=475Z^5$ V/cm. To observe the effects one can consider transitions to the ground state. If the nuclear spin is equal to zero in this case, then the line corresponding to the transition $2s_{1/2} \to 1s_{1/2}$ should split into two. The magnitude of the splitting is much less than the relaxation width of the level $2s_{1/2}$, with allowance for the Stark broadening[3]: $\Gamma_s^{(S)}=\Gamma_p\xi^2$, $\Delta E/\Gamma_s^{(S)}=\delta(0)\xi^{-1}=1.2\times 10^{-11}Q(ZN)\xi^{-1}$. The parameter ξ can vary in the range $\xi_0\leqslant\xi\leqslant 1$, where $\xi_0=6\times 10^{-8}Z^3$ is determined by the value of the intensity F at which the width $\Gamma_s^{(S)}$ becomes equal to the width Γ_s in the absence of the field. The width Γ_s is determined by the two-quantum width $\Gamma(2\gamma)=7\times Z^6$ sec^{-1}. In addition to the radiative width, it is necessary to take into account also the Doppler width Γ_D and the "Zeeman" width Γ_H. The latter is connected with the appearance of a magnetic field in the rest system of an atom moving in an electric field. Since the atoms move at random, the Zeeman effect leads to a line broadening equal to $\Gamma_H=(e/m)vF$, where v is the average velocity of the atoms. Γ_H and Γ_D are connected by the relation $\Gamma_H \approx \alpha(\alpha Z)^3\Gamma_D$, i.e., $\Gamma_H \ll \Gamma_D$. The Doppler width also exceeds the splitting significantly: $\Delta E/\Gamma_D=5\times 10^{-9} \times \xi Q Z^2 v^{-1}$ (cm/sec). Finally, observation of the effect may be hindered by the presence of systematic background magnetic fields, which also lead to a splitting of the levels. The critical intensity of these fields is $H_{cr}=\Delta E/\mu = 2\times 10^{-10}\xi Q(ZN)Z^4$ Oe, where μ is the magnetic moment of the electron.

We proceed now to mesic atoms. This is done in our formulas by using the relations[2]

$$\frac{L_\mu}{L_e} = 1.2\cdot 10^2\frac{m_\mu}{m_e};\quad \frac{\delta_\mu(0)}{\delta_e(0)} = \left(\frac{m_\mu}{m_e}\right)^3\frac{L_e}{L_\mu} = 0.9\cdot 10^{-2}\left(\frac{m_\mu}{m_e}\right)^2;$$

$$\frac{\Gamma_\mu}{\Gamma_e} = \frac{m_\mu}{m_e}.$$

The results for μ-mesic atoms are the following: $\Delta E/\Gamma_s = 4.8\times 10^{-9}\,Q(ZN)\xi^{-1}$, $F_0=2.6\times 10^9 Z^5$ V/cm, and $H_{cr} = 3.2\times 10^{-3}\,Q(ZN)Z^4$ Oe. The total width Γ_s for mesic atoms at $Z\geqslant 2$ is determined by the value of $\Gamma(2\gamma)$.

We now present a number of examples. For a hydrogenlike atom with $Z=16$, at $F\sim 10^6$ V/cm, we obtain $\Delta E = 2.2$ Hz, $\Delta E/\Gamma_s = 1.0\times 10^{-7}$, $\Delta E/\omega_s \sim 10^{-18}$, $\Delta E/\Gamma_D \sim 10^{-8}v^{-1}$ (cm/sec), $H_{cr}\sim 10^{-5}$ Oe, and $\omega_s = 2.5$ keV, where ω_s is the transition frequency. For a hydrogen mesic atom with $Z=2$, at $F\sim 10^7$ V/cm, we obtain $\Delta E = 0.32$ Hz, $\Delta E/\Gamma_s = 4.3\times 10^{-5}$, $\Delta E/\omega_s\sim 10^{-19}$, $\Delta E/\Gamma_D \sim 10^{-9}v^{-1}$ (cm/sec), $H_{cr}\sim 10^{-5}$ Oe, and $\omega_s = 8.4$ keV.

We now estimate the splitting of the levels $2s_{1/2}$ and $1s_{1/2}$ by a hyperweak CP-violating interaction: $\Delta E_{hw}(2s_{1/2}) = \epsilon(L/\Gamma)\Delta E_w(2s_{1/2}) \approx 10\epsilon\Delta E_w(2s_{1/2})$, where the subscripts hw and w pertain to the hyperweak and weak interactions, and $\epsilon = G_{hw}/G_w$. At $\epsilon\sim 10^{-3}$ we have $\Delta E_{hw}/\Delta E_w \sim 10^{-2}$. The ground state of the atom in the electrical field has the barrier width, but this width decreases exponentially with decreasing fields, and is negligibly small already at $F\sim 10^6$ V/cm. The ground level is therefore split only by the hyperweak interaction. The order of ΔE_{hw} is $10^{-11}Z^5$ Hz at $\epsilon\sim 10^{-3}$.

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