Parity nonconservation in transitions between hyperfine structure components of heavy atoms

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The circular polarization of the radiation in transitions between the hyperfine structure (hfs) components of heavy atoms is calculated. A possible experiment wherein this effect can be observed is indicated.

In a recent paper,[1] a realistic possibility was pointed out of observing a parity-nonconserving weak interaction between an electron and nucleons, by determining the rotation of the plane of polarization of light in heavy-metal vapor. It was noted that it is convenient to work at a frequency close to that of the usual $M1$ transition between the fine-structure component. Such an experiment would make it possible to observe, in weak interaction between an electron and a nucleon, a correlation between the electron spin and its momentum, i.e., and interaction of a leptonic axial current with a nucleonic vector.

Of no less interest would be the observation of parity nonconservation effects that depend on the spin of the nucleon. They are due to the interaction between the loptonic current and the nucleonic axial current. This effect might manifest itself in transitions between hfs components, which are also ordinary $M1$ transitions and are convenient from this point of view for the observation of the rotation of the plane of polarization.

Unfortunately, the parity-nonconservation effects turn out to be smaller here than in transitions between the fine-structure components. All the atomic mechanisms that lead to enhancement of the mixing of levels of different parity by a factor Z^2 [2] are active here, as before. However, since the effect is due to interaction of an electron with one unpaired nucleon and not with all the nucleons of the nucleons, as in the case of optical transitions, its value turns out to be, roughly speaking, smaller by a factor Z than in the optical band. However, the accuracies attained in modern centimeter-wave technology are much higher than in optics, so that the measurement of the parity-nonconservation effects in the radio band seems to be quite realistic[1)].

The Hamiltonian of the parity-nonconserving interaction of a relativistic electron with a pointlike nucleus will be written in the form

$$H = -\frac{G\hbar^3}{\sqrt{2}c}\,\delta(\mathbf{r})\,[Zq\gamma_5 + h < \vec{\sigma}_n > \vec{\alpha}]. \tag{1}$$

Here $G = 10^{-5}\ m^{-2}$ is the Fermi weak-interaction constant, m_p is the proton mass, $\vec{\sigma}_n$ is the unpaired-nucleon spin operator, $\gamma_5 = -i\gamma_0\gamma_1\gamma_2\gamma_3$, $\vec{\alpha} = \gamma_0\vec{\gamma}$, and γ_μ are Dirac matrices; the dimensionless constants q and h depend on the weak-interaction model.

It is easy to show that the interaction (1) can lead to a mixing of only the $s_{1/2}$ and $p_{1/2}$ one-electron states. The corresponding matrix element is

$$< s_{1/2}|H|p_{1/2} > = + \frac{iGm^2Z^2a^2}{\pi\sqrt{2}} R \frac{me^4}{2\hbar^2}(\nu_p\nu_s)^{-3/2}$$
$$\times \{ Zq - h\frac{2\gamma+1}{3} g_i\ [F(F+1) - i(i+1) - 3/4] \}\,. \tag{2}$$

Here m is the electron mass

$$\gamma = \sqrt{1 - a^2Z^2}, \quad R = \frac{4(2Zr_0/a)^{2\gamma-2}}{\Gamma^2(2\gamma+1)}\,,$$

a is the Bohr radius, r_0 is the radius of the nucleus, ν_p and ν_s are the effective quantum numbers of the p and s states, g_i is the coefficient of proportionality between $\langle\vec{\sigma}_n\rangle$ and the angular momentum of the nucleus i, and F is the total angular momentum of the atom. The circular polarization in the hyperfine transition is due only to the terms containing $F(F+1)$.

Calculation of the degree of circular polarization of the radiation ζ was carried out for cesium and thallium. Without dwelling on the details (see[2,1]) we note that in thallium the contribution made to the effect by the admixture of the $6s^26p^2$ terms with total angular momentum $J=\frac{1}{2}$ to the ground state $6s^26p_{1/2}$ is approximately equal to the contribution made by the ordinary excited states $6s^2ns$ (it suffices to confine oneself here to $n = 7$ or 8). As to the states that arise upon excitation of the electrons from the fully filled shells, allowance for them is in our case undoubtedly an exaggeration of the accuracy. For example, analysis of the polarizability of xenon shows that the corresponding dipole matrix elements are small.

The calculations yield $\zeta = 0.6\times10^{-9}h$ for cesium ($\lambda = 3.26$ cm) and $\zeta = -1.3\times10^{-8}h$ for thallium ($\lambda = 1.42$ cm).

According to the now-popular Weinberg model [6] with allowance for the experimental data on neutral currents with neutrino participation), $h = -0.24$. This prediction should not be given much significance, however. It is precisely in the determination of h that the experimental problem lies.

The presence of circular polarization of the radiation would lead to the appearance of parity nonconservation effects in the case of propagation of a radio wave in metal vapor. To this end, obviously, it is necessary that the populations of the upper and lower hfs levels be different. This difference can be attained by laser excitation of one of these levels. It is necessary here to exclude the possibility of optical orientation of the atoms. If we confine ourselves to the natural temperature-dependent population difference, then this will decrease the effects by a factor of several hundred.

What kind of effects are we dealing with? Different matrix elements of the emission of right-hand and left-hand quanta $M_\pm = M(1\pm\zeta/2)$ lead to different refractive indices for these quanta near the corresponding resonance:

$$n_\pm = 1 - \frac{\left(2\pi N|M_\pm|^2\right)}{[\hbar(\omega - \omega_0 + i\Gamma/2)]}\,, \tag{3}$$

where N is the density of the atoms; the population of the upper level is assumed to be small. When a plane-polarized wave is propagated, its polarization plane is rotated over the distance through an angle

$$\psi = \frac{\omega l}{2c}\,\mathrm{Re}\,(n_+ - n_-)\,. \tag{4}$$

The maximum of ψ is obviously reached at $|\omega - \omega_0| = \Gamma/2$.

In addition, owing to the difference in the absorption of the right and left polarizations, the wave becomes elliptically polarized. The ratio of the major and minor semi-axes is

$$\xi = \frac{\omega l}{2c}\,\mathrm{Im}(n_+ - n_-). \tag{5}$$

At a pressure higher than 10^{-2} mm, when the Doppler broadening is smaller than the impact width Γ, we obtain the following results:

1) For cesium: The cross section for the transfer of excitation by the upper hfs level is $\sigma = 2.3\times10^{-14}$ cm^2. [7] The absorption length is $l_0 = (2(\omega/c)\mathrm{Im}n)^{-1} = 12$ m, and $\psi_{max}/l = \zeta/2l_0 \approx 0.25\times10^{-10}h$ rad/m.

2) For thallium: We assume for σ the same value as in cesium. Then $l_0 = 35$ m and $\psi_{max}/l \approx 1.8\times10^{-10}h$ rad/m.

It is not convenient to work in the vicinity of the maximum of the effect with respect to frequency, particularly because we encounter here the usually most dangerous mechanism, that of the imitation of the effect on account of a random external magnetic field, viz., a difference between the resonance frequencies for the right- and left-polarized wave, due to the Zeeman splitting of the lines. Nonetheless, an external magnetic field leads to the appearance of optical activity, causing a mixing of terms with different F. To imitate the discussed effect, it suffices to have an average longitudinal magnetic field $\sim 2\times 10^{-5}h$ G in cesium and $\sim 3.2\times 10^{-4}h$ G in thallium.

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[1)] Even without the use of a modulation technique, the sensitivity in the measurement of the polarization-plane rotation in the radio band reaches 10^{-6}–10^{-8} rad.[3–5] In optics, the modulation technique can raise the sensitivity of the ellipsometric measurements, in any case, by three orders of magnitude.

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