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Asymmetry of breakup of optically active molecules by longitudinally polarized relativistic electrons

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We estimate the optical asymmetry produced in a racemic mixture of dextro- and levorotatory molecules under the influence of longitudinally polarized electrons. We show how this effect is connected with the known asymmetry of the photochemical action of circularly polarized light. The expected asymmetry of the order of 10^{-6} is in agreement with not all the experiments on the chemical action of polarized electrons that are naturally obtained in β decay.

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1. INTRODUCTION

The predominance of certain optically active molecules over their antipodes in living matter is a puzzle long troubling the physicists, chemists, and biologists. The discovery of parity nonconservation in weak interaction has raised hopes that the dextro- and levorotatory asymmetry in living matter can be connected with weak interaction (see Refs. 1 and 2).

In principle the situation may involve the energy contribution of weak interaction, particularly on account of neutral currents,[3-6] which shifts the thermodynamic equilibrium. Another variant is connected with the longitudinal polarization of the electrons produced in the β decay of radioactive elements. It is known that the degree of their polarization, of the order of $p/E = (E^2 - m^2c^4)^{1/2}/E$, approaches unity for relativistic electrons. The chemical reactions caused by such electrons can have a somewhat different probability for dextro- and levomolecules, and this can lead to the appearance of optical activity in an initially racemic mixture. A general review of the problem, including specific biological enhancement mechanisms, can be found in Ref. 7. The first to suggest the role of polarization of β particles was Ulbricht (see Refs. 1 and 2).

Experiment[8-11] yields contradictory results, from zero to several percent. In view of the difficulty of the experiments and the various possible experimental errors, an independent theoretical estimate of the possible effect is highly desirable. It must be kept in mind here that in the case of photochemical action of circularly polarized light the asymmetry has been incontrovertibly established and measured.[12-14]

In essence, the very fact of rotation of the plane of polarization proves the existence of the effect and provides an estimate of its magnitude. The rotation depends on the difference between the refractive indices of the right- and left-polarized light. The photochemical reaction is connected with the absorption of light, i.e., with the imaginary part of the refractive index. The dispersion relations, interconnect the real and imaginary parts.

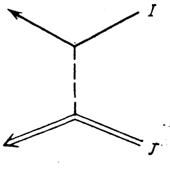
Direct measurements yield a photo-asymmetry of the order of several percent. Ulbricht considers the circular polarization of photons emitted in the course of bremmstrahlung, as well as their photochemical action. At an energy of one or several MeV, however, the direct chemical action is stronger than action via real intermediate photons. We consider therefore in the present note just the direct action of electrons on molecules in collision.

In the examination of the mechanism, we note that the action of the electron is due to its electromagnetic field. In the case of direct action one can also speak of photon exchange. Compared with the Ulbricht mechanism, the difference is that in the direct action the photon is virtual and the condition $E=cp$ is violated.

The idea of the calculation can be compared with the Williams-Weizsacker method, in which the Lorentz-transformed Coulomb field of the charge is regarded as an aggregate of virtual photons. The sought asymmetry of the reaction, due to the electron is expressed in terms of the photochemical asymmetry, which can be regarded as known. The principal result is that the asymmetry of the electron reaction is less than the asymmetry of the photon reaction in a ratio $v\hbar\omega/cE$, where v and E are the electron velocity and energy, and $\hbar\omega$ is the effective activation energy of the reaction. Thus, the expected asymmetry of the electron action is small, of the order of 10^{-6}.

2. DEPENDENCE OF THE CROSS SECTION ON THE LONGITUDINAL POLARIZATION OF THE ELECTRON

We consider the process of interaction of an electron with an asymmetrical molecule in first-order perturbation theory. The direct diagram is of the form



here I and J are the transfer currents of the electron and molecule, respectively. The exchange diagram differs from the direct one in that $D(k)$ is now replaced by $D(p)$, so that the exchange diagram is smaller than the direct one by a factor k^2/p^2, which in our case is $\ll 10^{-4}$. We therefore neglect the exchange effect.

For the square of the transition amplitude we have (see Ref. 15)

$$\begin{aligned}|M_{if}|^2&=e^4J^{\nu'}J^{*\mu'}\,\mathrm{Sp}\,\rho'\gamma^\nu\rho\gamma^\mu D_{\nu'\nu}D_{\mu'\mu}\\&=e^4J_{\nu'}J_{\mu'}^{*}D^{\nu'\nu}D^{\mu'\mu}[4p_\nu p_\mu-2(p_\nu k_\mu+k_\nu p_\mu)+2ime_{\nu\mu ij}a^ik^j],\end{aligned}\tag{1}$$

where

$$a^0=\mathbf{p}\boldsymbol{\xi}/m,\qquad \mathbf{a}=\boldsymbol{\xi}+\mathbf{p}(\mathbf{p}\boldsymbol{\xi})/m(E+m).$$

We choose the following gauge for the photon propagator:

$$D_{00}=0,\qquad D_{0\alpha}=0,$$

$$D_{\alpha\beta}=-\frac{4\pi}{k_0^2-k^2}\left(\delta_{\alpha\beta}-\frac{k_\alpha k_\beta}{k^2}\right).$$

Then (1) reduces to the form

$$\begin{aligned}|M_{if}|^2=\frac{16\pi^2e^4}{(k_0^2-k^2)^2}\Bigg\{&\left[4(\mathbf{Jp})^2-8\frac{(\mathbf{Jp})(\mathbf{Jk})(\mathbf{pk})}{k_0^2}+4(\mathbf{pk})^2(\mathbf{Jk})^2\right]\\&+2im\left(J_\alpha-k_\alpha\frac{(\mathbf{Jk})}{k_0^2}\right)\left(J_\beta^*-k_\beta\frac{(\mathbf{Jk})^*}{k_0^2}\right)e_{\alpha\beta\gamma}(a_\gamma k_0-a_0k_\gamma)\Bigg\}.\end{aligned}\tag{2}$$

We now consider the molecule transition current. Its orbital part is of the form

$$J_\alpha(k)=\frac{1}{2c}[\langle f|v_\alpha e^{-ikr}+e^{-ikr}v_\alpha|i\rangle].$$

If we expand the exponential and take additionally into account the spin part of the transition current, we obtain

$$eJ_\alpha(k_0,\ k)=ik_0d_\alpha+{}^1/_2k_0Q_{\alpha\beta}k_\beta+ie_{\alpha\beta l}k_\beta m_l.$$

Here d is the electric dipole moment, Q the electric quadrupole moment, and m the magnetic dipole moment. Averaging over the orientations of the molecules in space, we get

$$e^2\overline{J_\alpha(\mathbf{k})J_\beta^*(\mathbf{k})}=k_0^2\frac{d^2}{3}\delta_{\alpha\beta}+e_{\alpha\beta l}\frac{\mathbf{m}^*\mathbf{d}-\mathbf{m}\mathbf{d}^*}{3}k_lk_0=k_0^2A\delta_{\alpha\beta}+iBk_0e_{\alpha\beta l}k_l.\tag{3}$$

For optical transitions we have

$$\frac{B}{A}=2\,\mathrm{Im}\frac{dm}{d^2}\sim\alpha.$$

If we recognize that the main contribution to the decay cross section is made by photons with energy $\hbar\omega\sim Ry$, then we can choose as a rough estimate $B/A\sim\alpha$. If we start from the concepts of spatial dispersion, then we have for B/A the estimate $ka\sim10^{-2}-10^{-3}$, where a is the dimension of the molecule. Substituting (3) in (2) we get

$$|M_{if}|^2=\frac{16\pi^2e^2}{(k_0^2-k^2)^2}\left\{4A[p^2k_0^2-2E^2k_0^2+E^2k^2]+\frac{4mBk_0}{mp}(p^2-E^2k_0^2)\lambda\right\},\tag{4}$$

where λ is the helicity of the electron.

We consider now the case of a nonrelativistic electron. Then (4) reduces to the form

$$\frac{16\pi^2e^2}{k^4}\left\{(4Am^2+4mBk_0p\lambda)k^2-4mBk_0^3\frac{E'^2}{p}\lambda\right\};\tag{5}$$

from the first term in the braces we have

$$\eta_{\mathrm{el}}=\frac{\sigma_+-\sigma_-}{\sigma_++\sigma_-}=\frac{\hbar\omega}{mc^2}\frac{v}{c}\frac{B}{A}.\tag{6}$$

The contribution of the second term in the braces to η_{el} is an order of magnitude smaller than that of the first.

Thus, the degree of asymmetry of the decay cross section is

$$\eta_{\mathrm{el}}\sim\alpha^3v/c$$

($\alpha=1/137$ is the fine-structure constant). Here α^2 is obtained from the ratio of the spin-orbit interaction to the Coulomb interaction, and the additional power of α

corresponds to m/d. In the relativistic case we must be more careful with the expansion of the exponential. But this is most likely to influence only the value of σ, and in order of magnitude we have $\eta_{el} \sim \hbar\omega B/EA$, i.e., the effect begins to decrease in the ultrarelativistic case.

3. CHANGE OF THE ELECTRON POLARIZATION UPON DECAY OF MOLECULES

According to Ref. 15, the polarization of the electron as a result of one act of interaction is given by

$$a_t' = \frac{\mathrm{Sp}(\hat{p}'+m)\gamma_\nu(\hat{p}+m)(1-\gamma_5\hat{a})\gamma_\mu(\hat{p}'+m)\gamma^5\gamma^t A^{\nu\mu}}{2m\,\mathrm{Sp}(\hat{p}'+m)\gamma_\nu(\hat{p}+m)\gamma_\nu(\hat{p}+m)(1-\gamma_5\hat{a})\gamma_\mu A^{\nu\mu}}.$$

$$A^{\nu\mu} = D^{\nu\nu'} J_{\nu'} J_{\mu'}^* D^{\mu\mu'}.$$

A calculation accurate to second order in k/p has shown that the change of the longitudinal polarization is

$$\lambda' - \lambda = -\lambda^2 \frac{B}{A}\frac{\hbar\omega}{E}\frac{v}{c}. \qquad (7)$$

The obtained expression shows that the "reaction force" of the asymmetrical breakup of the molecules changes the electron polarization in the direction for which the breakup cross section is minimal. Actually, however, the electron loses its polarization, in absolute value, even when scattered by atoms. This effect is of the order of k^2/p^2 and leads to an order-of-magnitude decrease of the absolute value of the longitudinal polarization greater than (7).

The exchange effects in electron-electron scattering lead to a decrease of the polarization by a fraction k^4/p^4. When the energy of the incident electron approaches Ry, the longitudinal depolarization of the electron in the collisions should be close to unity.

4. CROSS SECTION OF DECAY OF AN ASYMMETRICAL MOLECULE UNDER THE INFLUENCE OF CIRCULARLY POLARIZED PHOTONS

The asymmetry of this process has been long known (see Refs. 12 and 13). The matrix element of the transition for photon absorption is of the form

$$e(2\pi/\omega)^{1/2} e_\mu J_{fi}^\mu(-k). \qquad (8)$$

In a transverse gauge we have $M_{fi} \propto \mathbf{e}\cdot\mathbf{J}$. From this, using

$$J_\alpha(-k) J_\beta^*(-k) = k_0^2 A \delta_{\alpha\beta} - iBk_0 k_t e_{t\alpha\beta}, \qquad (9)$$

we get for $\eta_{phot} = (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$

$$\eta_{phot} = -B/A. \qquad (10)$$

Stevenson[14] investigated decay under the influence of longitudinally polarized photons as a function of the solvent, temperature, and photon frequency. It turns out that, depending on the temperature and on the solvent, η_{phot} can undergo a severalfold change. On individual forbidden lines, η_{phot} can reach 10%, and in other regions it can have a value smaller by an order of magnitude. Comparing (6) and (10), we find that

$$\eta_{el}(\omega) = -\frac{\hbar\omega}{E}\frac{v}{c}\eta_{phot}(\omega). \qquad (11)$$

Such a rigid connection between η_{el} and η_{phot} should be preserved also in the presence of solvents. The accuracy of (11) might be limited only by the accuracy of the first born approximation, but for our case of collision of a fast electron with a molecule its accuracy is ~Ry/$E \sim 10^{-4}$. The accuracy of (11) is not connected with the correctness of the dipole expansion for the molecule transition current. The fact that the asymmetry of the process in which longitudinally polarized electrons participate should not be large has been noted in Ref. 9.

In conclusion we note the high desirability of performing simultaneous photon and electron experiments on the same substances. The authors thank B. Ya. Zel'dovich for a helpful discussion.

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