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Abstract

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ON THE ANOMALOUS ENERGY DEPENDENCE OF THE POLARIZATION OF RADIATION FROM ATOMS EXCITED BY AN ELECTRON BEAM

(Presented by Academician E. K. Zavoisky on 16 XI 1966)

Since the mid-1920s, when Skinner ([1]) and Skinner and Appleyard ([2]) first discovered the polarization of radiation arising upon bombardment of mercury atoms by a beam of electrons, there has been a sharp discrepancy between the theoretical and experimentally observed dependence of the polarization on the energy of the incident electrons. Whereas theory ([3–5]) predicts a monotonic dependence with a single maximum at an electron energy equal to the threshold energy, in experiment the polarization of light in the near-threshold region, as a rule, tends to zero ([1,2,6–8]). The anomalous behavior of the polarization in the near-threshold region has been discussed in a number of works ([4,9,10]), but so far no satisfactory theoretical explanation of this effect has been found ([11]).

We wish to show that the dip observed experimentally in the polarization of radiation at energies close to the threshold can be explained within the framework of a semiclassical picture of the collision. In this case the cause of the anomalous behavior of the polarization turns out to be the rotation of the quantization axis in the direction of the departing electron.

Let us consider the excitation of an atomic level nLI with energy E_{nLI}. Let us note, first, that anomalous polarization is observed at low energies E of the incident electrons ($10^{-2} \leq (E - E_{nLI})/E_{nLI} \leq 1$), to which rather small values of the orbital angular momenta l of the relative motion must correspond. At the same time, calculations show ([12]) that for $(E - E_{nLI})/E_{nLI} \geq 10^{-2}$ the contribution of the S-wave to excitation and scattering is negligibly small. If, moreover, $E - E_{nLI} \gg |E_{nLI} - E_{n,L\pm1,I}|$ (usually $|E_{nLI} - E_{n,L\pm1,I}| \lesssim 10^{-1}$ eV), then the interaction of the atom with the electron will have a dipole character ([13]), and for describing the scattering of electrons having orbital angular momentum of the relative motion $1 < l < n^2$ one may use classical mechanics ([14]).

It is essential, however, that for the excited atom collisions with $1 < l < n^2$ are in a certain sense adiabatic ([15]).

Indeed, the interaction of the atomic electron with a classical particle having charge Ze is written in the form

$$V_1'(t) = -\frac{Ze^2}{\sqrt{\mathbf{R}^2 + \mathbf{r}_a^2 - 2\mathbf{R}\cdot\mathbf{r}_a}}, \tag{1}$$

where $\mathbf{r}_a(r_a, Q_a, \varphi_a)$ is the radius vector of the atomic electron. The potential (1) depends on the angle φ_a, and therefore, generally speaking, the projection M of the angular momentum of the atom onto a distinguished direction will not be conserved. Let us pass to a coordinate system whose OZ axis at each instant of time is directed toward the charged particle. Suppose that the trajectory $\mathbf{R}$ of the charged particle lies in the XY plane and, as $t \to -\infty$, is parallel to the OZ axis. Then the wave function Ψ of the atom in the new coordinate system is related to the wave function Ψ' in the fixed coordinate system by the relation ([16])

$$\Psi = \exp(-i\hat{l}_x\Phi)\Psi',$$

where Φ is the polar angle of the radius vector of the exciting particle. In the rotating reference frame the potential (1) turns out to be independent of φ_a:

$$V_1(t) = -\frac{Ze^2}{\sqrt{R^2 + r_a^2 - 2Rr_a\cos\theta_a}}. \tag{1a}$$

However, in this coordinate system an additional interaction appears [16]

$$V_2 = \hbar\hat{l}_x\, d\Phi/dt, \tag{2}$$

which causes transitions between sublevels with different M. If the characteristic magnitude of the matrix elements $\langle nLM|V_2|n'L'M \pm 1\rangle$ is smaller than the characteristic magnitude of $\langle nLM|V_1|n'L'M\rangle$, then, in the coordinate system rotating with the passing particle, the magnetic quantum number is conserved. In other words, magnetic adiabaticity holds.

The criterion for magnetic adiabaticity of the collision is not difficult to obtain if, for simplicity, the trajectory of the exciting particle is taken to be rectilinear, $\mathbf{R} = \mathbf{R}(0, \rho, vt)$, and if one restricts oneself to the dipole approximation for estimating the characteristic magnitude of the matrix element V_1. Then $\Phi = \operatorname{arc\,tg}\rho/vt$, $V_1 \sim n^2 a_0 e^2/(\rho^2 + v^2t^2)$, and the criterion is written as

$$l < \frac{2n^3}{\sqrt{(I+M)(I-M+1)}}\,\frac{m_0}{m_e}, \tag{3}$$

where m_0 is the mass of the incident particle, and m_e is the electron mass.

Usually the polarization of spectral lines arising upon excitation of levels with $I \leqslant 3$ is investigated. In this case the range of applicability of criterion (3) and the criterion for classical motion $V(\rho) \gg \hbar v/\rho$ [14] essentially coincide, and one may assert that the directions of the quantization axes of atoms excited as a result of collisions with electrons having angular momentum of relative motion $1 < l < n^2$ are distributed in proportion to the differential effective cross section for inelastic scattering of an electron by an atom $d\sigma_{\text{inel}}(\vartheta)/d\Omega$, calculated in the classical approximation. The energy dependence of the radiation polarization [3] is

$$\Pi = \frac{I_\parallel - I_\perp}{I_\parallel + I_\perp} = \frac{\Pi_0(3\cos^2\vartheta - 1)}{2 - \Pi_0(1 - \cos^2\vartheta)}, \tag{4}$$

where ϑ is the angle between the quantization axis and the initial direction of the beam; Π_0 is the polarization of the light when observed relative to the quantization axis, which may be obtained, for $|E_{nLI} - E_{n,L\pm1,I}| \ll E - E_{nLI} \ll n^2 E_{nLI}$, by averaging $\cos^2\vartheta$ over $d\sigma_{\text{inel}}(\vartheta)/d\Omega$, specified by the classical formulas (formula (80) from Ref. [17]). For $|E_{nLI} - E_{n\pm1,I}| \ll E - E_{nLI} \ll E_{nLI}$, the cross section $d\sigma_{\text{inel}}(\vartheta)/d\Omega$ is described with sufficient accuracy by expression [17]:

$$\frac{d\sigma_{\text{inel}}(\vartheta)}{d\Omega} = \frac{\sigma_0\sqrt{E - E_{nLI}}}{E_1^{1/2}E^{3/2}\left(2E - E_{nLI} - 2\cos\vartheta\sqrt{E(E - E_{nLI})}\right)^{3/2}}, \tag{5}$$

where E_1 is the kinetic energy of the electron in the atom. It is not difficult to see that, for the radiation polarization in this region, one obtains a linear dependence on the electron energy:

$$\Pi = \frac{3\Pi_0}{3 - \Pi_0}\,\frac{E - E_{nLI}}{E_{nLI}}. \tag{6}$$

Thus, the behavior of the radiation polarization as a function of the electron energy may be given the following qualitative interpretation. At the energy $E = E_{nLI}$ the polarization is maximal, $\Pi = \Pi_0$, since in

in inelastic scattering only the S-wave is present ([3–5]). As the energy increases, other partial waves begin to appear, and the polarization decreases. For $E - E_{nLI} \gtrsim |E_{nLI} - E_{nL\pm1,I}|$, several orbital angular momenta ([13]) will be present in inelastic scattering with equal probability, and the polarization should disappear ([18,19]). Taking into account that collisions with $1 < l < n^2$ are magnetically adiabatic in character and, moreover, can be described by classical mechanics, the disappearance of polarization can also be explained by the isotropy of the inelastically scattered electrons. The increase of polarization for $E_{nLI} \gg E - E_{nLI} \gg |E_{nLI} - E_{nL\pm1,I}|$ is connected with the fact that in this region the inelastically scattered electrons are directed predominantly forward, and this anisotropy increases with energy. The second maximum of polarization corresponds to the maximum anisotropy. With a further increase of energy ($E \gtrsim 2E_{nLI}$), the number of electrons scattered perpendicular to the initial direction of the beam increases ([17]), and for $E \gtrsim n^2 E_{nLI}$ the contribution of electrons with $l > n^2$ becomes appreciable. Both of these factors contribute to a decrease in polarization.

Of interest is a direct experimental test of the adiabaticity of collisions with $1 < l < n^2$. One may, for example, measure by the coincidence method the polarization of the radiation not with respect to the direction of the incident electron, but with respect to the direction of the scattered electron. In this case, in the region $|E_{nLI} - E_{nL\pm1,I}| \ll E - E_{nLI} < E_{nLI}$, the magnitude of the polarization should be close to Π_0.

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Note: Figure translations are in progress. See original paper for figures.