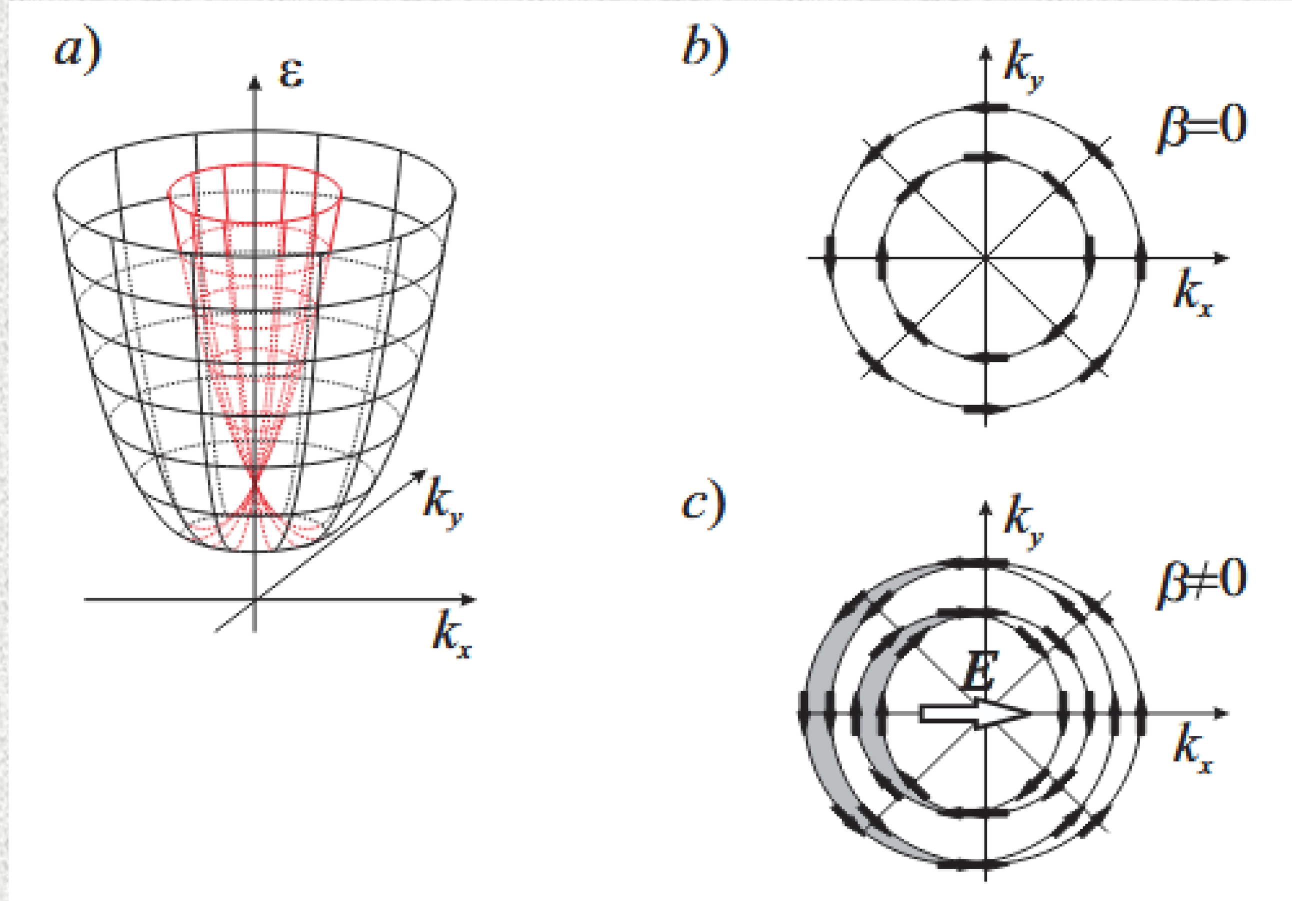
Spin Hall effect in aluminum and platinum

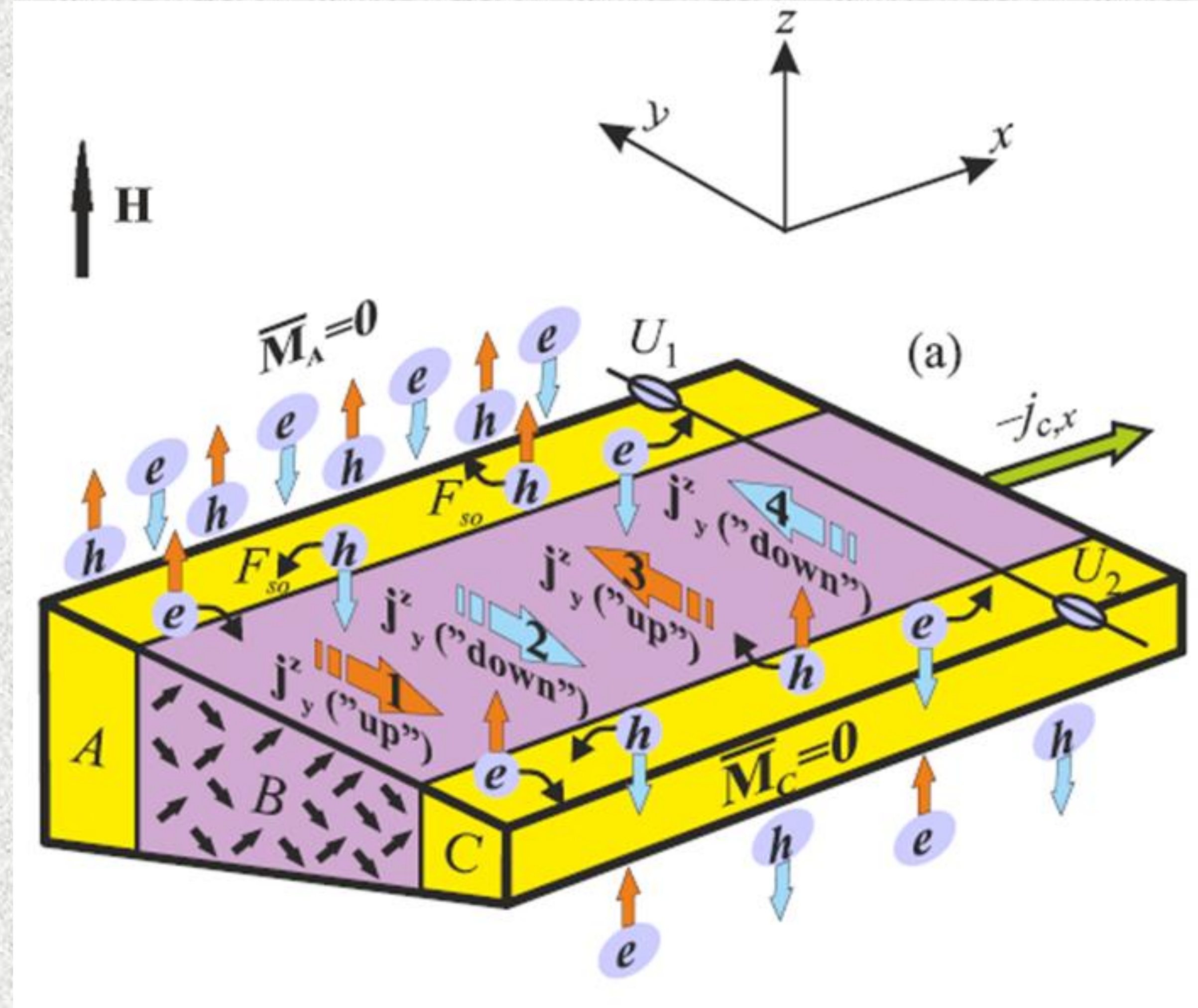
Yu. N. Chiang (Tszyan), M. O. Dzyuba

ILTPE NASU, Ukraine

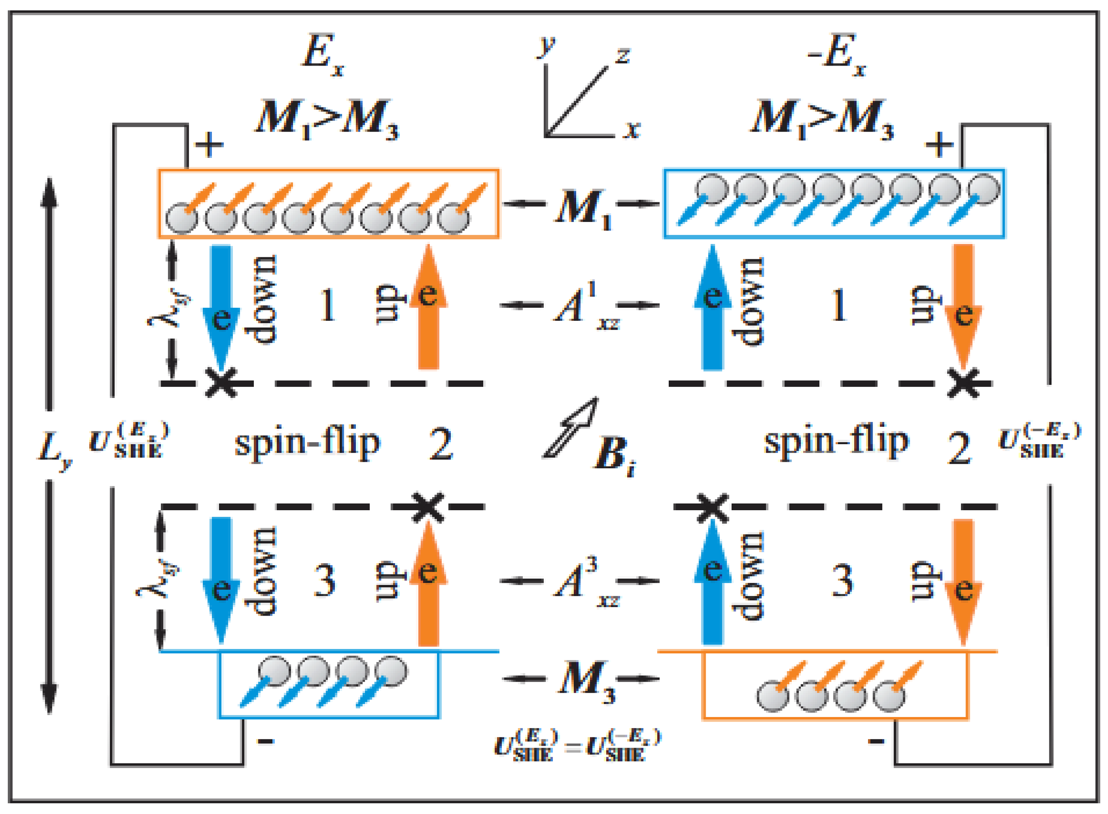
E-mail:dzyuba@ilt.kharkov.ua



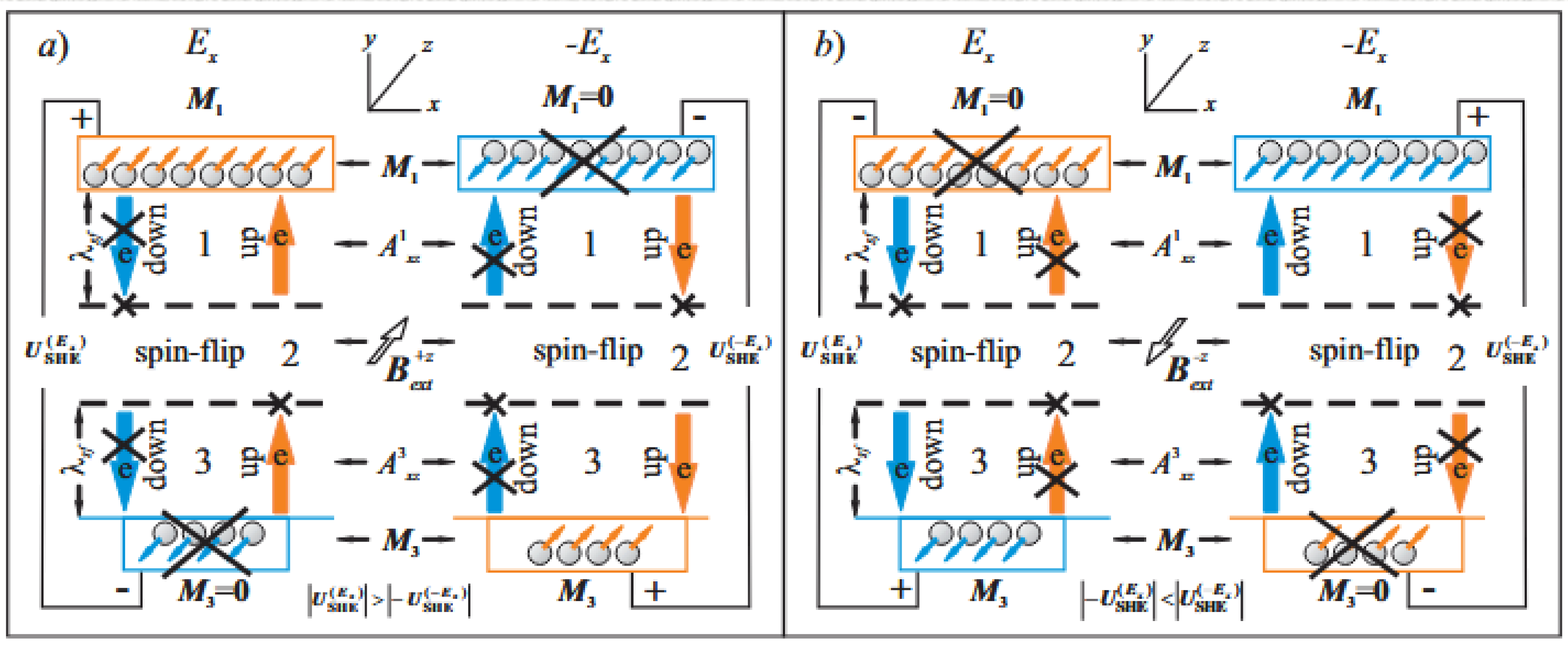
Spin-orbit interaction (SOI) is the interaction between an effective magnetic field $\boldsymbol{B}_i$, which arises in the coordinate system of a moving electron, **and** its magnetic moment (spin). This effective magnetic field is rigidly coupled to the electron's momentum $\boldsymbol{p}$ and mass $\boldsymbol{m}$, characterizing a typical relativistic effect in a solid $\boldsymbol{B_i} \sim \boldsymbol{E} \times \boldsymbol{p} / mc^2$. Figure 1 shows the orientation of spins in eigenstates (b) for the relativistic Rashba effect (without an external magnetic field) and under an applied electric field (c). If an electron is in an electric field $\boldsymbol{E}$ that breaks structural inversion symmetry, the Rashba SOI contribution to the effective Hamiltonian, induced by the spin splitting of energy bands, can be expressed as: $\boldsymbol{H}_{\mathbf{SO}} = \beta e[\hat{\sigma} \times \boldsymbol{k}]\boldsymbol{E}$. In the absence of external magnetic fields, the $\boldsymbol{B_i}$ field enables the manifestation of the spin Hall effect (SHE) in the presence of an electric field $\boldsymbol{E}$.



Previously, we proposed the asymmetric sample geometry illustrated on this figure, which establishes a non-equilibrium spin distribution along the edges. To induce a transverse spin-charge imbalance for direct spin measurements, we use samples with a variable thickness (***d***) along the ***y***-axis (transverse to current $\boldsymbol{j_{c,x}}$). This asymmetric shape creates a difference in the total number of charges between the thin and thick boundaries. Crucially, the total transverse voltage is determined by the net number of charges, not their local density.



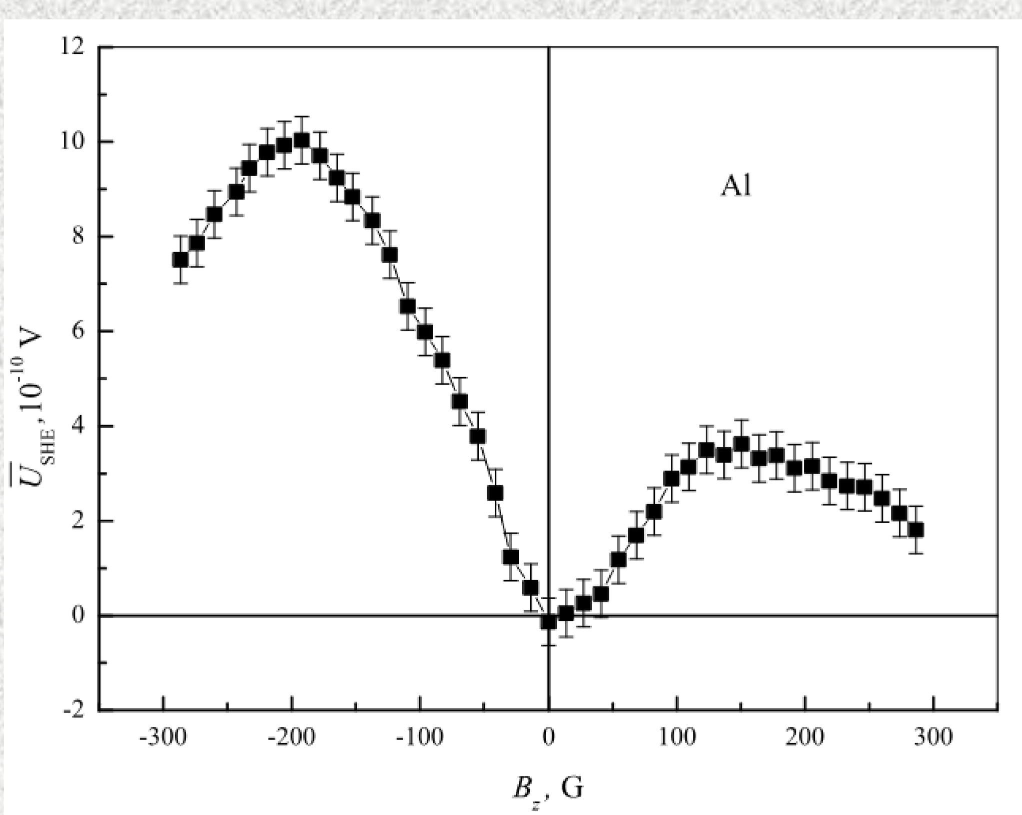
This figure illustrates an edge spin accumulation mechanism in paramagnetic (Al, Pt) samples, showing a spin-charge voltage ($\boldsymbol{U_y}$) that is independent of the electric field's polarity and a spin magnetization ($|\boldsymbol{M_1}$ - $\boldsymbol{M_3}|$) that reverses sign. This scheme highlights the relativistic Rashba contribution to the spin Hall effect (SHE) when accounting for spin relaxation, providing a refined, technically accurate description of the proposed mechanism.



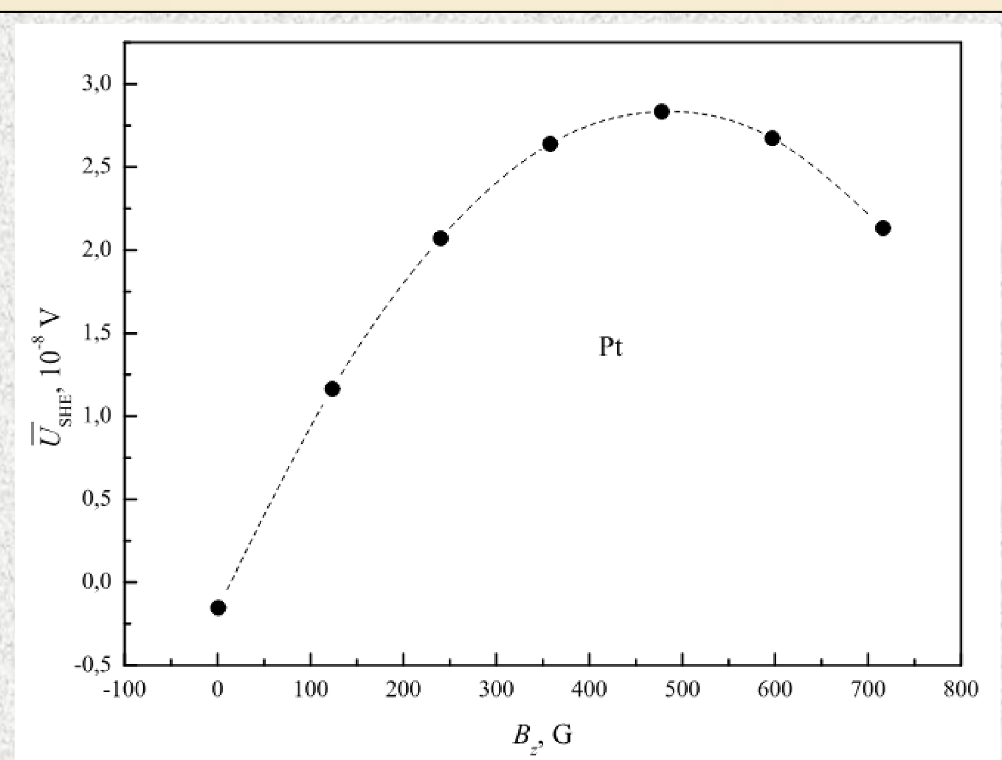
This figure illustrates edge spin accumulation in external magnetic ($\boldsymbol{B_{ext}}$) and electric ($\boldsymbol{E}$) fields, accounting for spin current discontinuity near boundaries ($\lambda_{sf} < \boldsymbol{L_y}$) and spin-flip scattering. By averaging measurements with opposite electric field directions at fixed magnetic fields, the symmetric ($\boldsymbol{U_{CHE}}$) contribution is eliminated, yielding the specific spin-charge SHE voltage.

$$\overline{U}_{\mathbf{SHE}}^{+B_z} = \frac{1}{2}\left[U_{\mathbf{SHE}}^{+E_x} - U_{\mathbf{SHE}}^{-E_x}\right]^{+B_z} = \frac{1}{2}\left[U_y^{+E_x} + U_y^{-E_x}\right]^{+B_z}$$

$$\overline{U}_{\mathbf{SHE}}^{-B_z} = \frac{1}{2}\left[U_{\mathbf{SHE}}^{-E_x} - U_{\mathbf{SHE}}^{+E_x}\right]^{-B_z} = \frac{1}{2}\left[U_y^{+E_x} + U_y^{-E_x}\right]^{-B_z}$$



The slides display the calculated curves for the relativistic spin Hall effect in aluminum and platinum versus the external magnetic field. Clearly, these curves differ qualitatively from the nearly linear dependence of the $\boldsymbol{U_{CHE}}$ contribution, agreeing well with the close-to-parabolic behavior discussed earlier work.



These SHE values yield the actual ratio of the spin-orbit relativistic energy shifts in both metals.

$$\frac{\beta^{Pt}}{\beta^{Al}} \geq \frac{H_{\mathbf{SO}}^{Pt}}{H_{\mathbf{SO}}^{Al}} \cdot \frac{\sigma_y^{Al}}{\sigma_y^{Pt}} = \frac{U_{\mathbf{SHE}}^{Pt}}{U_{\mathbf{SHE}}^{Al}} \cdot \frac{\sigma_y^{Al}}{\sigma_y^{Pt}} \sim 40 \times 3 = 120$$

This pronounced difference in the Rashba contributions directly confirms that the spin-orbit interaction is much stronger in Pt than in Al, driving the spin-orbit splitting of their energy bands.

Conclusion. We investigated the behavior of the relativistic spin Hall effect in Al and Pt paramagnets in both intrinsic and external magnetic fields, obtaining evidence of spin polarization in the direction of the external field. We considered only those measurements where the contribution of the classical Hall effect during reversal could be considered completely symmetric in magnitude with an accuracy no less than the value of the sought spin Hall effect. A comparison of the spin-orbit interaction in aluminum and platinum was performed.