Nuclear spin-orbit interaction in ternary fission

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Plan:

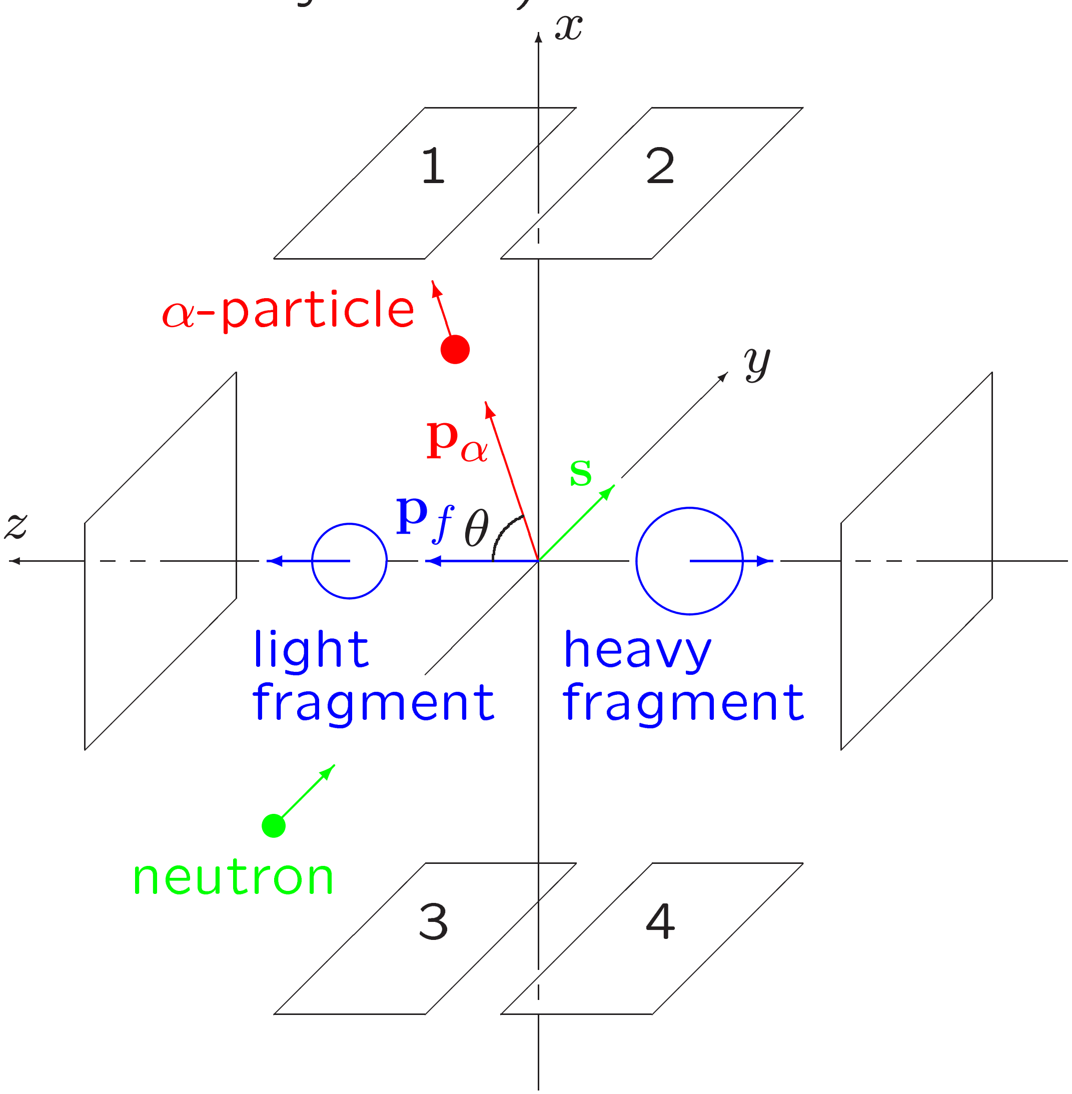
1) T-odd angular correlations in ternary fission

2) model description of these correlations by spin-orbit interaction

3) evidences for target spin effects and their interpretation

4) specification for the model with spin-orbit interaction for ternary fission

Asymmetries ($\sim 10^{-3}$) in fission with third particle emission (α-particle, if in ternary fission):



$$D_{13}(\theta) = \frac{N_1 - N_3}{N_1 + N_3}$$

$$D_{24}(\pi - \theta) = \frac{N_2 - N_4}{N_2 + N_4}$$

$$D = \frac{(N_1 + N_2) - (N_3 + N_4)}{(N_1 + N_2) + (N_3 + N_4)} = $$

$$= \frac{D_{13} + \lambda D_{24}}{1 + \lambda} \approx \frac{D_{13} + D_{24}}{2}$$

$$\lambda = \frac{N_2 + N_4}{N_1 + N_3} \approx 1$$

(y,z)-Transverse asym.: T-effect ("TRI-effect"): $D_{13} \simeq D_{24} \simeq D$ (n+^{233}U)

z-Reverse asym.: R-effect ("ROT-effect"): $D_{13} \simeq -D_{24} \Rightarrow D \simeq 0$ (n+^{235}U)

Short list of articles:

T-effect (in ternary fission for α particle as the third particle):

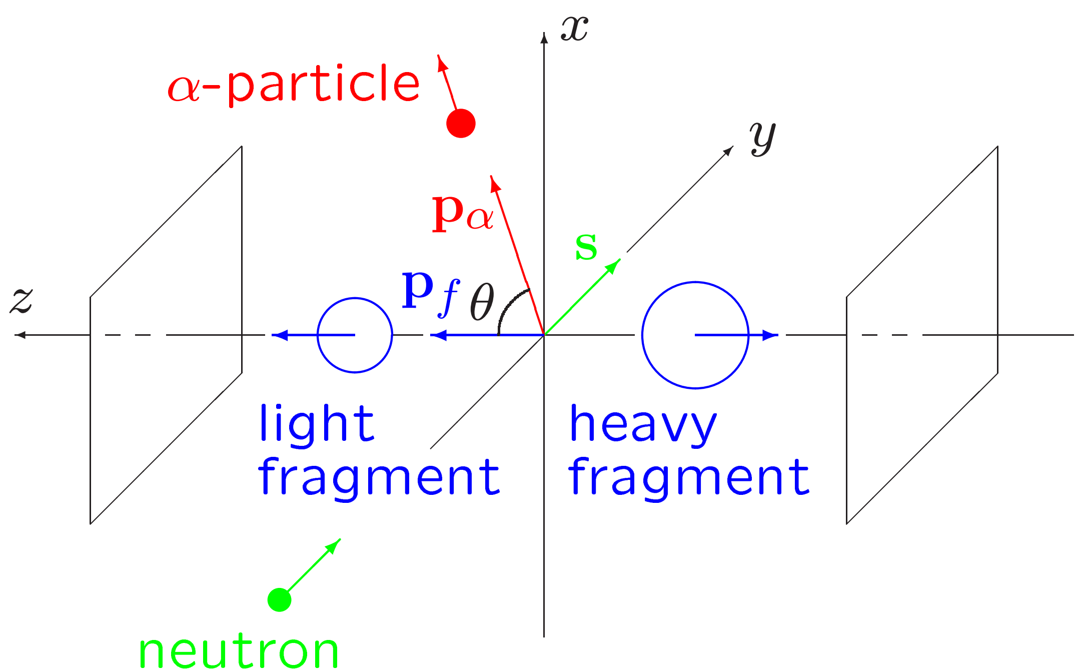
P. Jesinger et al., Nucl. Instr. Meth. Phys. Res. A. **440**, (2000) 618

P. Jesinger et al. Phys. At. Nucl. **65**, (2002) 630

R-effect: (in ternary fission for α particle as the third particle):

F. Goennenwein et al., Phys. Lett. B. **652**, (2007) 13

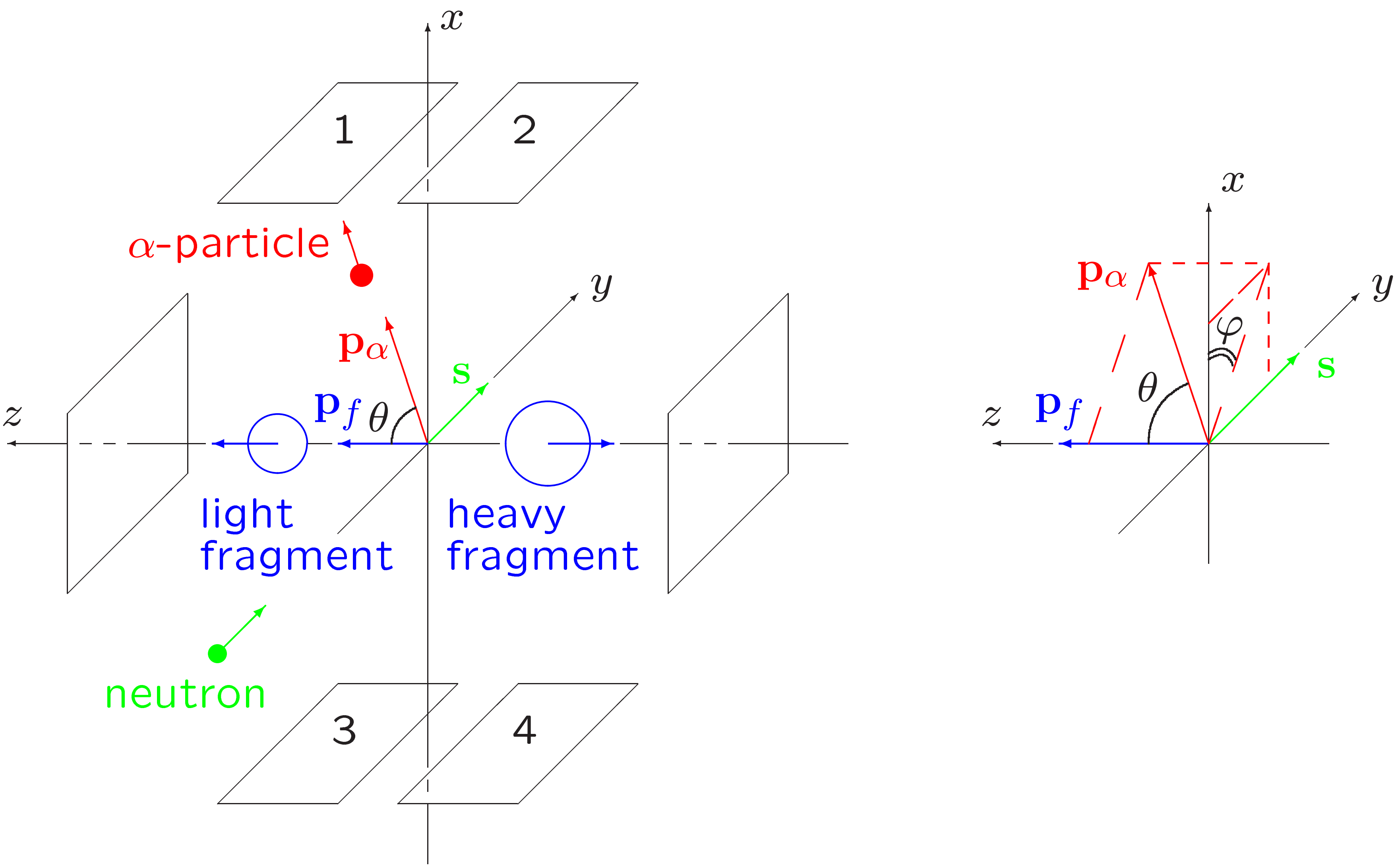
Model with spin-orbit interaction (A.L.Barabanov. Proc. 9-th ISINN, Dubna, 2001, P. 93; arXiv: 0712.3543):



$$\frac{dw(\theta,\varphi,E_\alpha)}{d\Omega\, dE_\alpha} \sim \sum_{M_f} \left| \int_0^\infty \langle \psi^{(-)}_{\mathbf{p}_\alpha} \Psi_{JM_f} | \frac{dV(t)}{dt} | \psi_{\alpha i} \Psi_J \rangle e^{i\omega_{fi}t} dt \right|^2 ,$$

$$V = V_0 + (V_{Jl}(\mathbf{J}\mathbf{l}_\alpha) + (\mathbf{J}\mathbf{l}_\alpha)V_{Jl}) , \quad \mathbf{J} = \mathbf{J}_L + \mathbf{J}_H + \mathbf{L} \sim \mathbf{s}$$

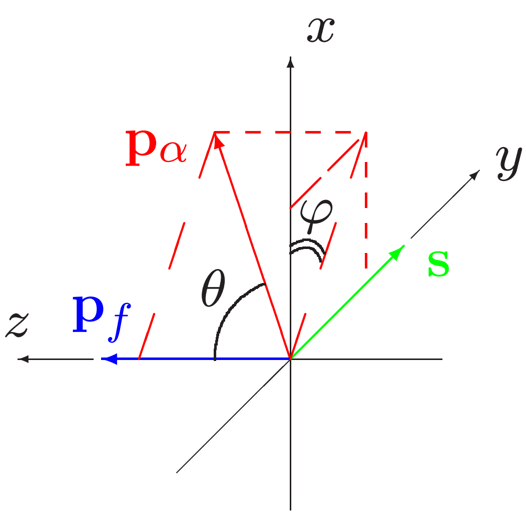
Model with spin-orbit interaction (A.L.Barabanov. Proc. 9-th ISINN, Dubna, 2001, P. 93; arXiv: 0712.3543):



$$\frac{dw(\theta,\varphi,E_\alpha)}{d\Omega\, dE_\alpha} = W_0(\theta) + p(J)\cos\varphi\,(W_1(\theta) + W_2(\theta)),$$

T- and R-effects are of the same nature:

$$\frac{dw(\theta,\varphi,E_\alpha)}{d\Omega\, dE_\alpha} = W_0(\theta) + p(J)\cos\varphi\,(W_1(\theta) + W_2(\theta)),$$



$$W_0(\theta) = \sum_{Q=0,1,2...} (2Q+1)a_Q(E_\alpha)P_Q(\cos\theta),$$

$$W_1(\theta) = \sum_{Q=1,3...} (2Q+1)b_Q(E_\alpha)P^1_Q(\cos\theta),$$

$$W_2(\theta) = \sum_{Q=2,4...} (2Q+1)b_Q(E_\alpha)P^1_Q(\cos\theta),$$

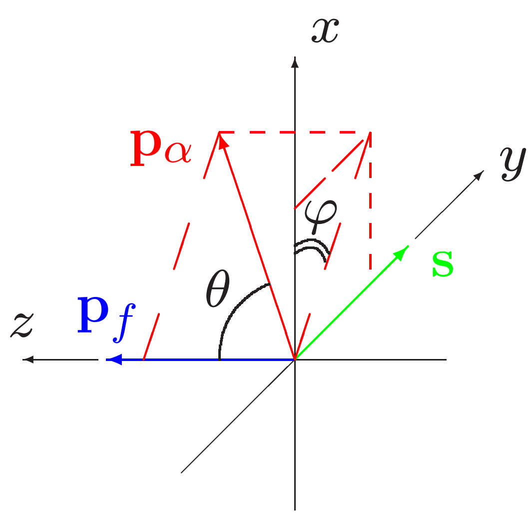
$$P^1_Q(\cos\theta) = \sin\theta\,\frac{dP_Q(\cos\theta)}{d\cos\theta},$$ therefore: $$W_1(\theta) = W_1(\pi-\theta)$$ $$W_2(\theta) = -W_2(\pi-\theta)$$

if $W_2(\theta) \simeq 0 \quad \Rightarrow \quad D_{13} \simeq D_{24} \simeq D \quad \Rightarrow$ T-effect (n+^{233}U)

if $W_1(\theta) \simeq 0 \quad \Rightarrow \quad D_{13} \simeq -D_{24}$ (D$\simeq$ 0 !) $\Rightarrow$ R-effect (n+^{235}U)

3- and 5-fold correlations (T-odd):

$$\frac{dw(\theta,\varphi,E_\alpha)}{d\Omega\, dE_\alpha} = W_0(\theta) + p(J)\cos\varphi\,(W_1(\theta) + W_2(\theta)),$$



$$W_1(\theta) = \sum_{Q=1,3\ldots} (2Q+1) b_Q(E_\alpha) P_Q^1(\cos\theta),$$

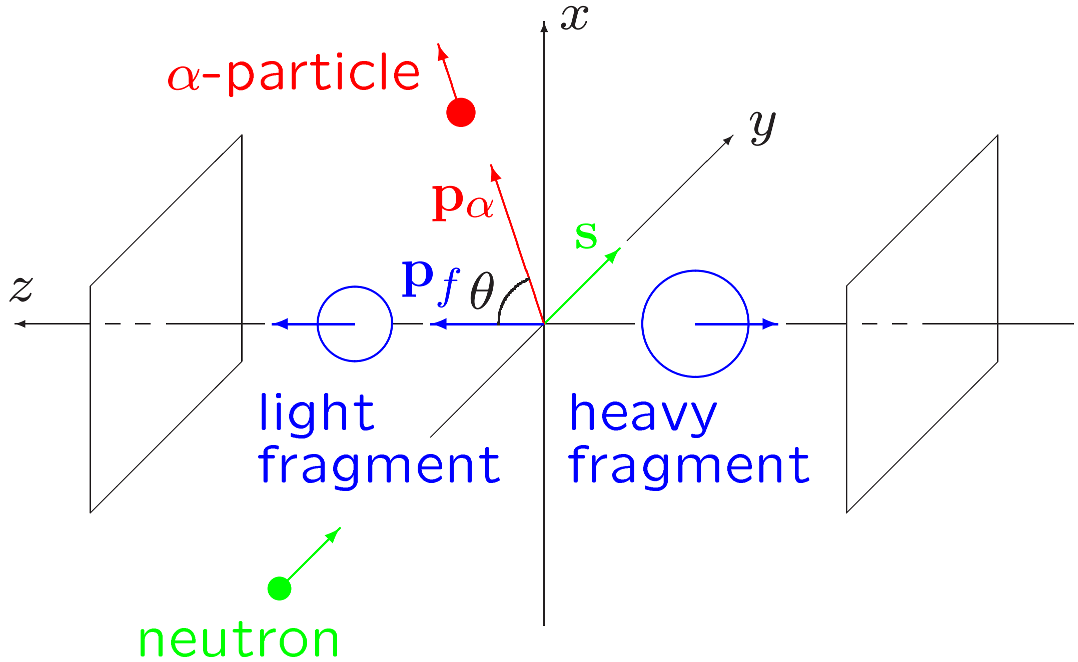
$$W_2(\theta) = \sum_{Q=2,4\ldots} (2Q+1) b_Q(E_\alpha) P_Q^1(\cos\theta),$$

$$\cos\varphi\, W_1(\theta) = 3\, b_1(E_\alpha) \underbrace{\cos\varphi\,\sin\theta}_{\overbrace{(\mathbf{p}_\alpha[\mathbf{s}\times\mathbf{p}_f])}^{|||}} + \ldots \quad \Rightarrow \quad \text{T-effect } (\text{n}+{}^{233}\text{U})$$

$$\cos\varphi\, W_2(\theta) = 15\, b_2(E_\alpha) \underbrace{\cos\varphi\,\sin\theta\,\cos\theta}_{\overbrace{(\mathbf{p}_\alpha[\mathbf{s}\times\mathbf{p}_f])(\mathbf{p}_\alpha\mathbf{p}_f)}^{|||}} + \ldots \quad \Rightarrow \quad \text{R-effect } (\text{n}+{}^{235}\text{U})$$

Are there some evidences for spin (target spin!) − orbit interaction?

What is a nature of such interaction?



$$\frac{dw(\theta,\varphi,E_\alpha)}{d\Omega\, dE_\alpha} \sim \sum_{M_f} \left| \int_0^\infty \langle \psi^{(-)}_{\mathbf{p}_\alpha} \Psi_{JM_f} | \frac{dV(t)}{dt} | \psi_{\alpha i} \Psi_J \rangle e^{i\omega_{fi}t} dt \right|^2 ,$$

$$V = V_0 + (V_{Jl}(\mathbf{J}\mathbf{l}_\alpha) + (\mathbf{J}\mathbf{l}_\alpha)V_{Jl}) \,, \quad \mathbf{J} = \mathbf{J}_L + \mathbf{J}_H + \mathbf{L} \sim \mathbf{s}$$

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Spin-Orbit and Target Spin Effects in Helion Elastic Scattering*

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(Received 28 August 1972)

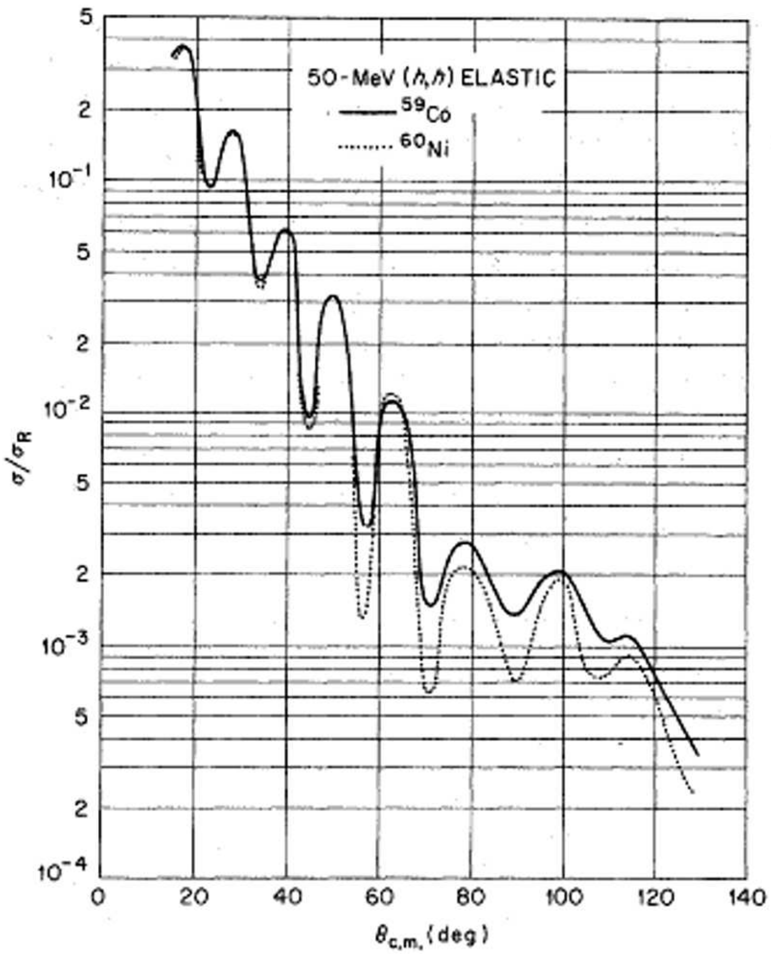

FIG. 5. Angular distributions for 50-MeV helion elastic scattering from ^{59}Co and ^{60}Ni. The plot for each target was obtained by drawing a smooth curve through the experimental data.

$I = \frac{7}{2}$ for ^{59}Co

$I = 0$ for ^{60}Ni

TARGET-SPIN EFFECTS ON ELASTIC SCATTERING CROSS SECTIONS*

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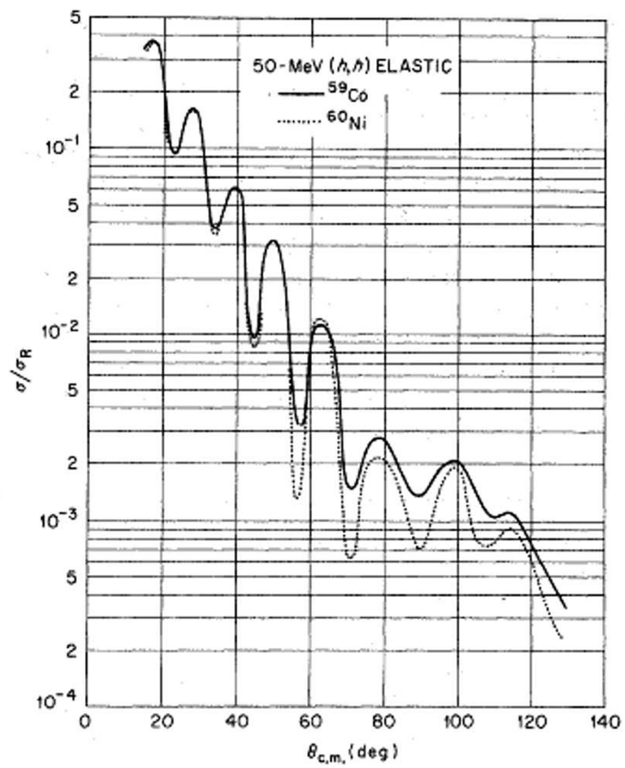
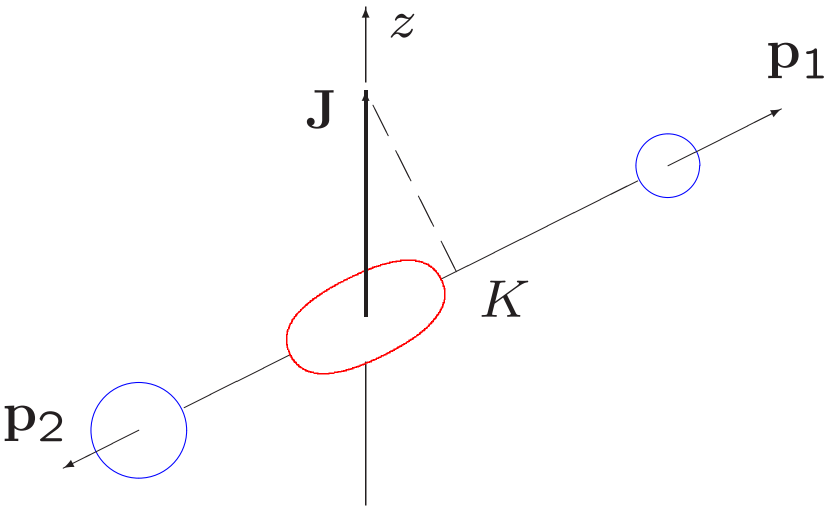
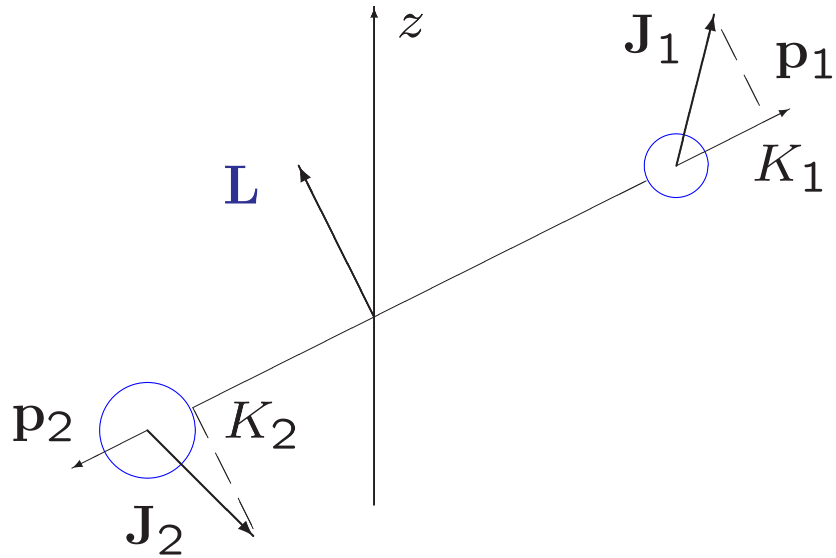


FIG. 5. Angular distributions for 50-MeV helion elastic scattering from ^{59}Co and ^{60}Ni. The plot for each target was obtained by drawing a smooth curve through the experimental data.

$$|\mathrm{odd}, IM\rangle = \alpha|(\mathrm{even}, 0), j = I; M\rangle + \sum_{L,j} \beta_{Lj}|(\mathrm{even}, L), j; IM\rangle. \qquad (1)$$

$$\sigma_{\mathrm{el}}(\mathrm{odd}) \approx \sigma_{\mathrm{el}}(\mathrm{even}) + \sum_{L} \frac{(2\alpha\beta_{LI})^2}{2L+1}\, \sigma_{\mathrm{inel}}(\mathrm{even}, 0^+ \to L^+) \qquad (2)$$





A. Bohr, in *Proc. Int. Conf. on the Peaceful Uses of Atomic Energy, Geneva, 1955*

V.M. Strutinsky, ZhETF **30**, 606 (1956)

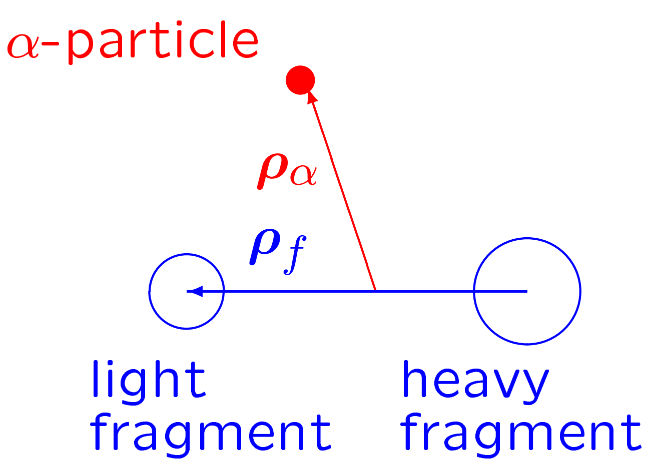
$$\begin{array}{ccccccc} \mathbf{J} & \rightarrow & \mathbf{J}_1 & + & \mathbf{J}_2 & + & \mathbf{L} \\ K & \rightarrow & K_1 & + & K_2 & & \end{array}$$

$$V = V_0 + (V_{Jl}(\mathbf{J}\mathbf{l}_\alpha) + (\mathbf{J}\mathbf{l}_\alpha)V_{Jl})\,, \quad \mathbf{J}\mathbf{l}_\alpha = (\mathbf{J}_1 + \mathbf{J}_2 + \mathbf{L})\mathbf{l}_\alpha \quad \rightarrow \quad \mathbf{L}\mathbf{l}_\alpha$$

Model with hyperspherical harmonics for three particle in the output channel:

Usual description of reactions (input wave + output waves):

$$\Psi \to \sum_{\lambda_\alpha} a(\lambda_\alpha) \left(\frac{u^{(-)}_{\alpha l}}{r_\alpha} \varphi^{\alpha}_{\lambda_\alpha} + \sum_{\beta} \left(\frac{m_\beta k_\beta}{m_\alpha k_\alpha} \right)^{1/2} \sum_{\lambda_\beta} S_J(\lambda_\alpha \to \lambda_\beta) \frac{u^{(+)}_{\beta l_\beta}}{r_\beta} \varphi^{\beta}_{\lambda_\beta} + \right.$$
$$\left. + \sum_{\gamma} \frac{k_\gamma^2 (\pi/2)^{1/2}}{(m_\alpha k_\alpha)^{1/2}} \sum_{\lambda_\gamma} S_J(\lambda_\alpha \to \lambda_\gamma) \frac{H^{(+)}_{N+2}(k_\gamma \rho_\gamma)}{(k_\gamma \rho_\gamma)^2} \, |JM;\lambda_\gamma\rangle \right) .$$

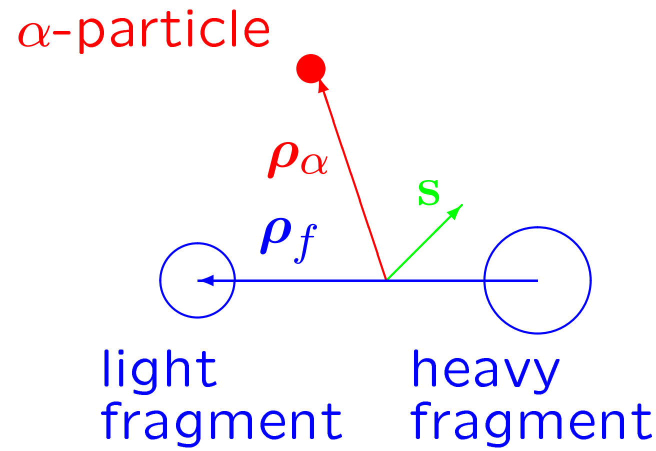


$$\rho_f = \rho \sin\vartheta, \quad \rho_\alpha = \rho \cos\vartheta,$$

$$|JM;\lambda_\gamma\rangle \sim (\sin\vartheta)^{l_f} (\cos\vartheta)^{l_\alpha} P_n^{L_f+\frac{1}{2}, l_\alpha+\frac{1}{2}}(\cos 2\vartheta) \times$$
$$\times \sum C^{J_0 M_0}_{JM l_\alpha m_\alpha} C^{JM}_{L_f m_f F f} Y_{l_\alpha m_\alpha}(\boldsymbol{\rho}_\alpha) Y_{L_f m_f}(\boldsymbol{\rho}_f) \, |Ff\rangle$$

$$N = 2n + l_\alpha + l_f$$

Differential cross section
for ternary fission:



$$\frac{d\sigma_f}{d\Omega_f\, d\Omega_\alpha} = \frac{\pi\lambda^2}{4\pi} \sum_{J_0 J_0'} g_{J_0'} \sum_{Q=0,1} U(IsJ_0'Q, J_0 s)\tau_Q'(s) \times$$

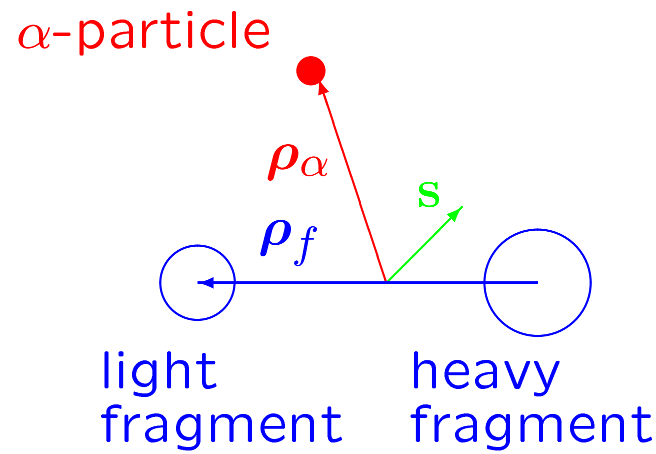
$$\sum_{L_f L_f' l_\alpha l_\alpha' n n' J J' F} S_{J_0}(0\tfrac{1}{2} \to L_f l_\alpha N J F) S^*_{J_0'}(0\tfrac{1}{2} \to L_f' l_\alpha' N' J' F) \times$$

$$\sum_{\Lambda_f \Lambda_\alpha} \hat{\Lambda}_f \hat{\Lambda}_\alpha \hat{l}_\alpha' \hat{J}' \hat{J} C^{L_f 0}_{L_f' 0 \Lambda_f 0} C^{l_\alpha 0}_{l_\alpha' 0 \Lambda_\alpha 0} U(FJ'L_f\Lambda_f, L_f'J) \begin{Bmatrix} J_0 & J & l_\alpha \\ J_0' & J' & l_\alpha' \\ Q & \Lambda_f & \Lambda_\alpha \end{Bmatrix} \times$$

$$\left(\int_0^{\pi/2} (\sin\vartheta)^{L_f + L_f' + 2} (\cos\vartheta)^{l_\alpha + l_\alpha' + 2} P_n^{L_f + \frac{1}{2}, l_\alpha + \frac{1}{2}}(\cos 2\vartheta) P_{n'}^{L_f' + \frac{1}{2}, l_\alpha' + \frac{1}{2}}(\cos 2\vartheta) d\vartheta \right)$$

$$(4\pi)^{1/2} \sum_{q \lambda_f \lambda_\alpha} C^{Qq}_{\Lambda_f \lambda_f \Lambda_\alpha \lambda_\alpha} Y^*_{Qq}(\mathbf{s}) Y_{\Lambda_f \lambda_f}(\boldsymbol{\rho}_f) Y_{\Lambda_\alpha \lambda_\alpha}(\boldsymbol{\rho}_\alpha)$$

Differential cross section
for ternary fission:



$$\frac{d\sigma_f}{d\Omega_f\, d\Omega_\alpha} = \ldots\ \underbrace{(4\pi)^{3/2} \sum_{q\lambda_f\lambda_\alpha} C^{Qq}_{\Lambda_f\lambda_f\Lambda_\alpha\lambda_\alpha} Y^*_{Qq}(\mathbf{s}) Y_{\Lambda_f\lambda_f}(\boldsymbol{\rho}_f) Y_{\Lambda_\alpha\lambda_\alpha}(\boldsymbol{\rho}_\alpha)}_{\substack{\parallel\!| \\ \overbrace{\phi^Q_{\Lambda_f\Lambda_\alpha}(\mathbf{s},\boldsymbol{\rho}_f,\boldsymbol{\rho}_\alpha)}}}$$

$$\phi^1_{11}(\mathbf{s},\boldsymbol{\rho}_f,\boldsymbol{\rho}_\alpha) \sim (\boldsymbol{\rho}_\alpha[\mathbf{s}\times\boldsymbol{\rho}_f]) \quad \Rightarrow \quad \text{T-effect } (\text{n}+{}^{233}\text{U})$$

$$\phi^1_{22}(\mathbf{s},\boldsymbol{\rho}_f,\boldsymbol{\rho}_\alpha) \sim (\boldsymbol{\rho}_\alpha[\mathbf{s}\times\boldsymbol{\rho}_f])(\boldsymbol{\rho}_\alpha\boldsymbol{\rho}_f) \quad \Rightarrow \quad \text{R-effect } (\text{n}+{}^{235}\text{U})$$

Summary

1. Both T- and R-effects (in particular, 3- and 5-fold correlations) in ternary fission, apparently, are due to spin-orbit interaction that mixes exit states (final state interaction).

2. Interaction of α-particle with collective degrees of freedom of the fissioning nucleus (interaction of $\mathbf{l}_\alpha$ and $\mathbf{L}_f$), apparently, gives dominant contribution to the spin-orbit interaction.