Coulomb mixing of continuum states in ternary fission

A.L. Barabanov

Kurchatov Institute, Moscow 123182, Russia

Coulomb mixing of continuum states in ternary fission

or

A philosophy of the angular correlations

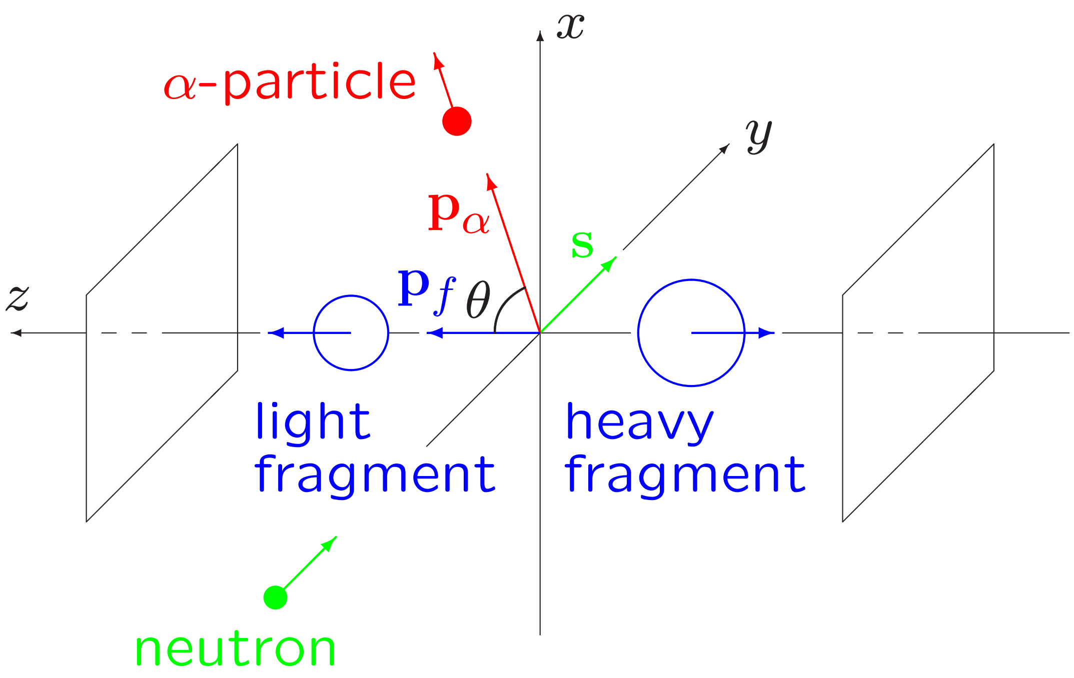
A.L. Barabanov

Kurchatov Institute, Moscow 123182, Russia

T-odd (but not TRI-violating!) angular correlations in neutron-induced ternary fission: both effects $\sim 10^{-3}$

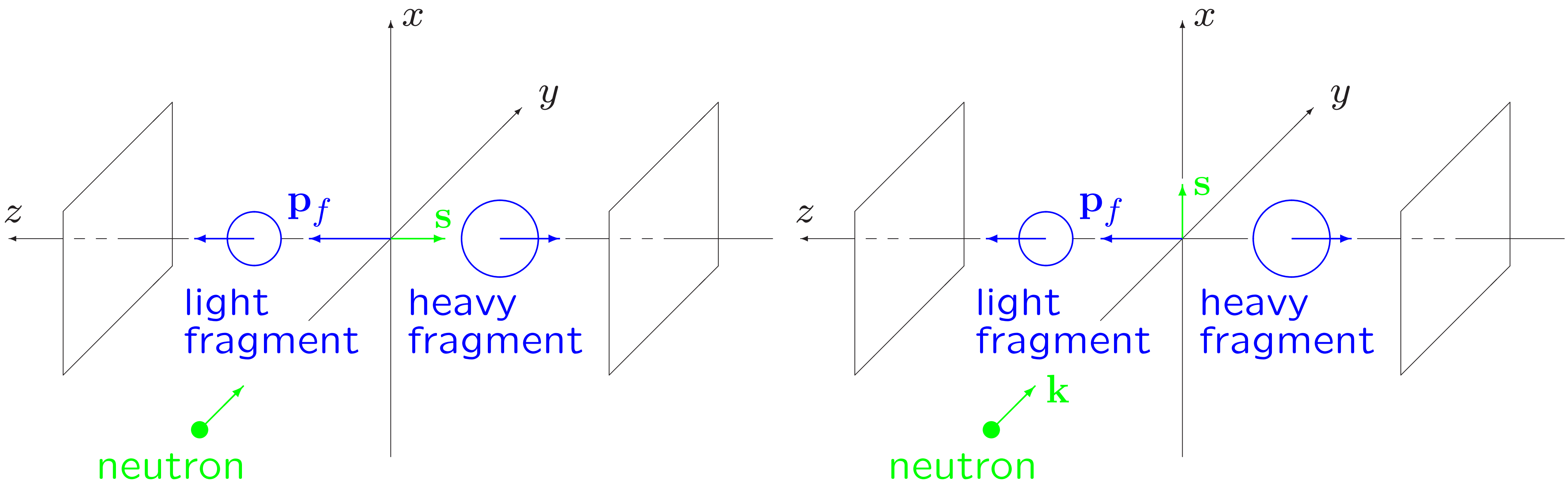
P. Jesinger et al., Nucl. Instr. Meth. Phys. Res. A. **440** 618 (2000): T-effect

F. Goennenwein et al., Phys. Lett. B. **652** 13 (2007): R-effect

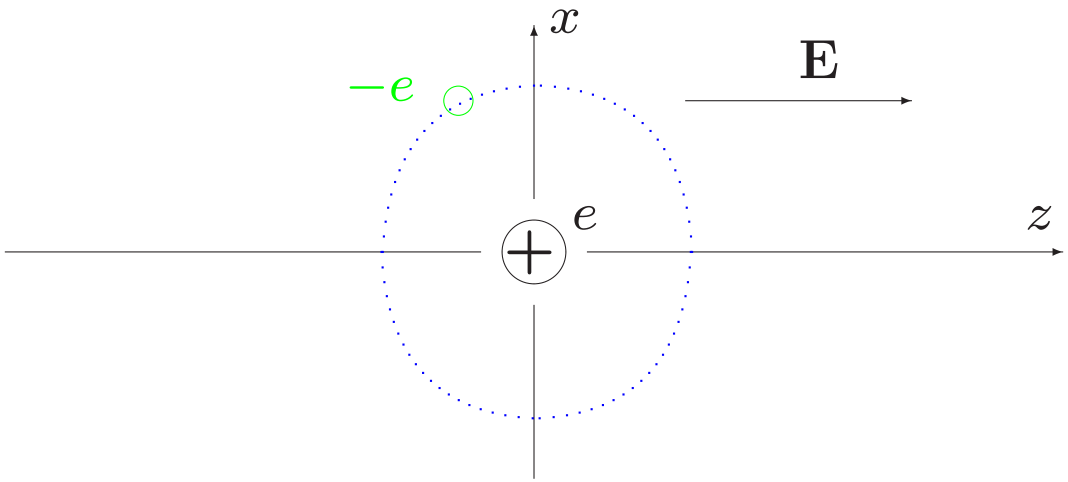


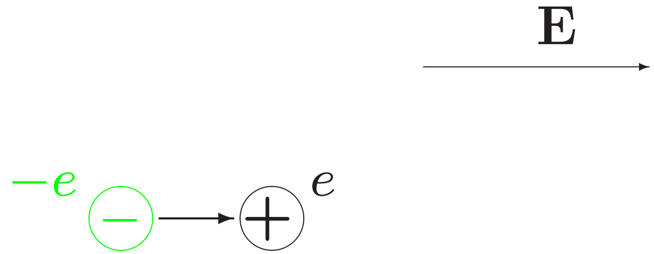
$$\frac{d\sigma}{d\Omega_f d\Omega_\alpha} = \frac{\sigma_0}{(4\pi)^2} + \ldots + \underbrace{\sigma_T \left(\mathbf{n}_\alpha \left[\mathbf{n}_s \times \mathbf{n}_f\right]\right)}_{\text{T-effect (2000)}} + \underbrace{\sigma_R \left(\mathbf{n}_\alpha \left[\mathbf{n}_s \times \mathbf{n}_f\right]\right)\left(\mathbf{n}_\alpha \mathbf{n}_f\right)}_{\text{R-effect (2007)}} + \ldots$$

P-odd and P-even angular correlations in neutron-induced binary fission



$$\frac{d\sigma}{d\Omega_f} = \frac{\sigma_0}{4\pi} + \ldots + \underbrace{\sigma_{PV}\left(\mathbf{n}_f \mathbf{n}_s\right)}_{\text{P-odd}} + \underbrace{\sigma_{LR}\left(\mathbf{n}_f\left[\mathbf{n}_k \times \mathbf{n}_s\right]\right)}_{\text{P-even}} + \ldots$$

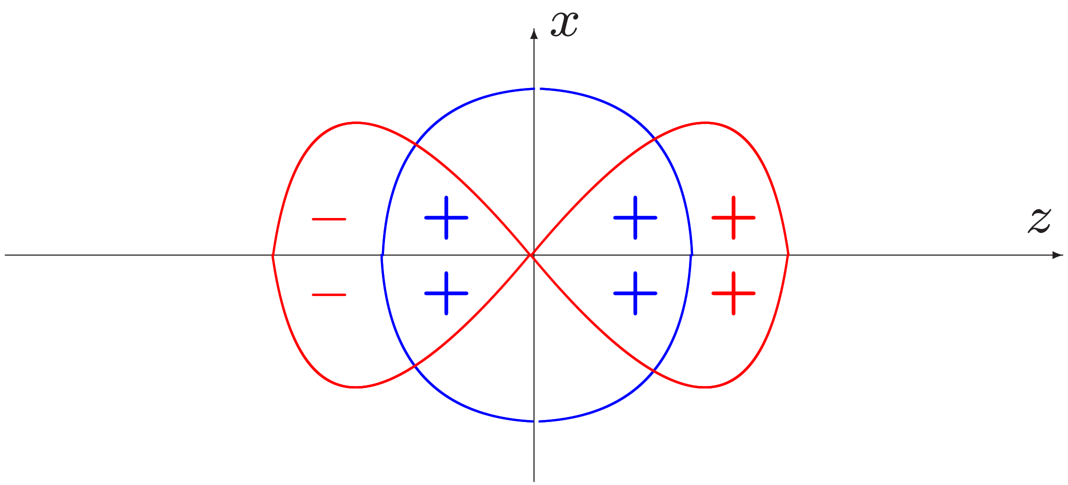


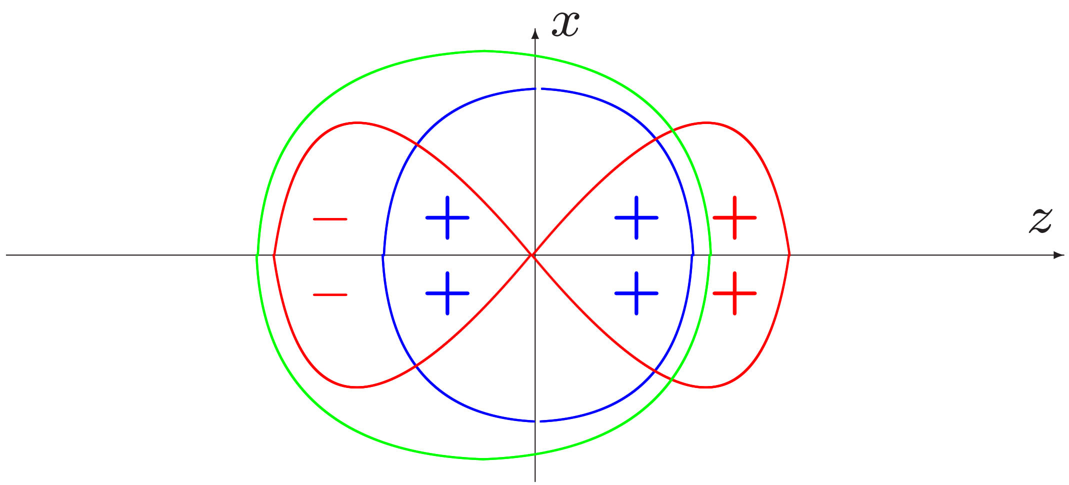


$$\mathbf{d} \sim \mathbf{E}$$

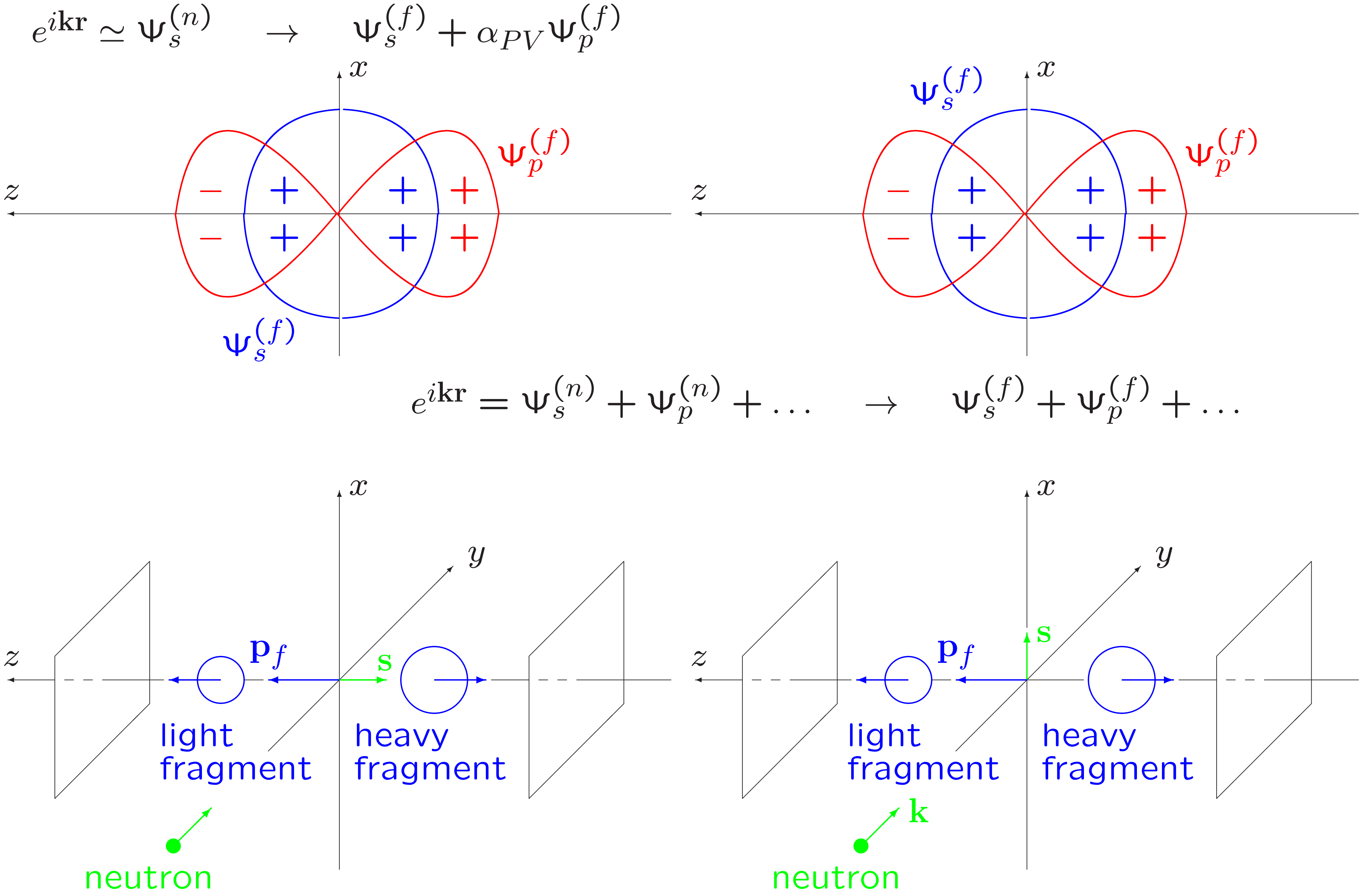
$$\hat{V} = -\mathbf{E}\hat{\mathbf{d}} = -e\mathbf{E}\mathbf{r} \quad \rightarrow \quad \Psi(\mathbf{r}) \simeq \Psi_{1s}(\mathbf{r}) + \Psi_{2p0}(\mathbf{r}) \underbrace{\frac{\langle \Psi_{2p0} | \hat{V} | \Psi_{1s} \rangle}{E_{1s} - E_{2p}}}_{\alpha < 0}, \quad \mathbf{E}_{1s} < \mathbf{E}_{2p}$$

$$\Psi_{1s}(\mathbf{r}) \sim \mathbf{e}^{-\frac{r}{a}} \mathbf{Y}_{00}(\mathbf{n}) \sim \mathbf{e}^{-\frac{r}{a}}, \qquad \Psi_{2p0}(\mathbf{r}) \sim \mathbf{r}\,\mathbf{e}^{-\frac{r}{2a}} \mathbf{Y}_{10}(\mathbf{n}) \sim \mathbf{r}\,\mathbf{e}^{-\frac{r}{2a}} \cos\theta$$



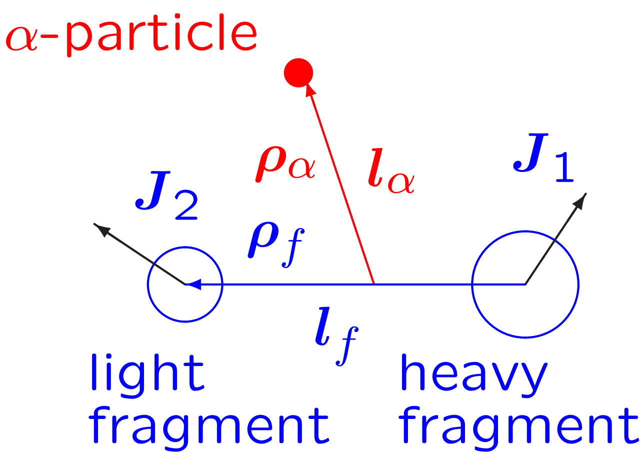


$$\Psi(\mathbf{r}) \simeq \Psi_{1s}(\mathbf{r}) - |\alpha| \Psi_{2p0}(\mathbf{r})$$



$e^{i\mathbf{kr}} \simeq \Psi_s^{(n)} \quad \rightarrow \quad \Psi_s^{(f)} + \alpha_{PV} \Psi_p^{(f)}$
x
z
$\Psi_s^{(f)}$
$\Psi_p^{(f)}$
$e^{i\mathbf{kr}} = \Psi_s^{(n)} + \Psi_p^{(n)} + \dots \quad \rightarrow \quad \Psi_s^{(f)} + \Psi_p^{(f)} + \dots$
y
$\mathbf{p}_f$
$\mathbf{s}$
light fragment
heavy fragment
neutron
$\mathbf{k}$

Hyperspherical harmonics for three (free) particles:



$$\boldsymbol{l}_f + \boldsymbol{l}_\alpha = \mathbf{L}, \quad \boldsymbol{J}_1 + \boldsymbol{J}_2 = \mathbf{F}, \quad \mathbf{L} + \mathbf{F} = \mathbf{J}$$

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

$$\Psi^{(+)}_{\lambda_t}(\boldsymbol{\rho}_f, \boldsymbol{\rho}_\alpha) = R^{(+)}_N(\rho)\,\varphi_{\lambda_t}(\vartheta, \mathbf{n}_f, \mathbf{n}_\alpha)$$

$$\lambda_t = (l_f, l_\alpha, N, L, F),$$

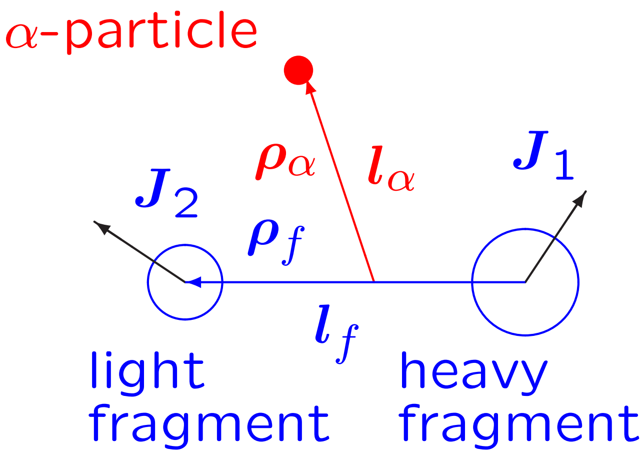
$$N = 2n + l_f + l_\alpha, \quad n = 0, 1, 2, \ldots$$

$$\varphi_{\lambda_t}(\vartheta, \mathbf{n}_f, \mathbf{n}_\alpha) = \sum_{\mu f} C^{JM}_{L\mu F f}\, i^N \Phi^{l_f l_\alpha}_{NL\mu}(\vartheta, \mathbf{n}_f, \mathbf{n}_\alpha) \sum_{M_1 M_2} C^{Ff}_{J_1 M_1 J_2 M_2}\, \psi_{J_1 M_1} \psi_{J_2 M_2}$$

$$\Phi^{l_f l_\alpha}_{NL\mu}(\vartheta, \mathbf{n}_f, \mathbf{n}_\alpha) \sim (\sin\vartheta)^{l_f} (\cos\vartheta)^{l_\alpha} P_n^{l_f + \frac{1}{2}\, l_\alpha + \frac{1}{2}}(\cos 2\vartheta) \times$$

$$\times \sum_{m_f m_\alpha} C^{L\mu}_{l_f m_f l_\alpha m_\alpha} Y_{l_f m_f}(\mathbf{n}_f) Y_{l_\alpha m_\alpha}(\mathbf{n}_\alpha)$$

Three (interacting) particles:



$$\boldsymbol{\rho}_f \sim \mathbf{r}_2 - \mathbf{r}_1\,, \quad \boldsymbol{\rho}_\alpha \sim \mathbf{r}_3 - \frac{A_1\mathbf{r}_1 + A_2\mathbf{r}_2}{A_1 + A_2}$$

$$\widehat{V} = \widehat{V}_{12} + \widehat{V}_{13} + \widehat{V}_{23}\,, \quad \widehat{V}_{ij} = \frac{Z_i Z_j e^2}{|\mathbf{r}_i - \mathbf{r}_j|}$$

l_f and l_α are not conserved!

$$\lambda_n = (l_n, j_n, J, M) \quad \to \quad \lambda_t = (l_f, l_\alpha, N, L, F)$$

$$\Psi^{(+)}_{\lambda_n}(\boldsymbol{\rho}_f, \boldsymbol{\rho}_\alpha) = \sum_{\lambda_t} R^{(+)}_{\lambda_n\lambda_t}(\rho)\,\varphi_{\lambda_t}(\vartheta, \mathbf{n}_f, \mathbf{n}_\alpha) \quad \to$$

$$\to \quad \sum_{\lambda_t} S(\lambda_n \to \lambda_t) R^{(+)}_N(\rho)\,\varphi_{\lambda_t}(\vartheta, \mathbf{n}_f, \mathbf{n}_\alpha) \equiv \sum_{\lambda_t} S(\lambda_n \to \lambda_t)\Psi^{(+)}_{\lambda_t}(\boldsymbol{\rho}_f, \boldsymbol{\rho}_\alpha)$$

System of coupled radial equations for neutron and ternary fission channels:

$$\begin{cases} \left(\frac{d^2}{dz^2}+\frac{5}{z}\frac{d}{dz}-\frac{N(N+4)}{z^2}+1\right)R^{\lambda_n LF}_{l_f l_\alpha N}(z)- \\ \quad -\sum\limits_{l'_f l'_\alpha N'}\langle\varphi_{l_f l_\alpha NLF}|\frac{2\widehat{V}}{\hbar^2 k_t^2}|\varphi_{l'_f l'_\alpha N'LF}\rangle R^{\lambda_n LF}_{l'_f l'_\alpha N'}(z)-\frac{2W^{\lambda_n}_{\lambda_t}(z)}{\hbar^2 k_t^2}R_{\lambda_n}(z)=0, \\ \\ \left(\frac{d^2}{dz^2}+\frac{2}{z}\frac{d}{dz}-\frac{l(l+1)}{z^2}+1\right)R_{\lambda_n}(z)-\sum\limits_{l_f l_\alpha N}\frac{2W^{\lambda_n}_{\lambda_t}(z)}{\hbar^2 k_n^2}R^{\lambda_n LF}_{l_f l_\alpha N}(z)=0, \end{cases}$$

where $z=k_t\rho$ and $z=k_n r$, with a boundary condition:

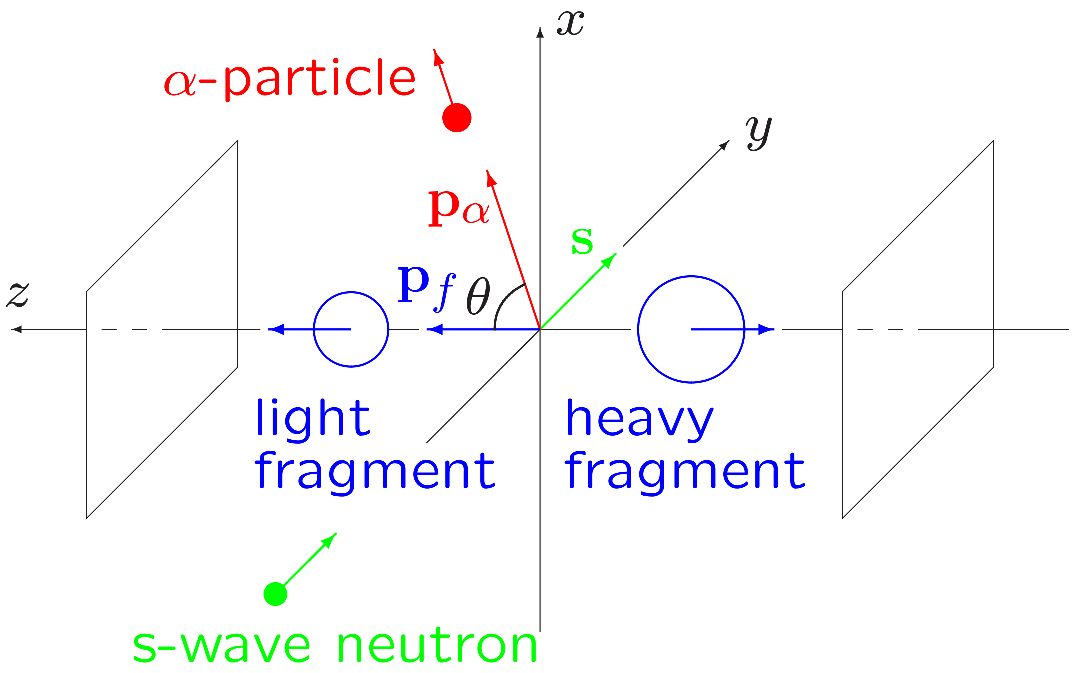
$$R_{\lambda_n}(z)=h_l^{(-)}(z)+S_J(\lambda_n\to\lambda_n)h_l^{(+)}(z).$$

Summary

1. Angular correlations in ternary fission are due to superposition (mixing) of the exit wave functions with opposite parities.

2. Coulomb repulsion of fragments and light charged particle (α-particle) seems provide the needed mixing.

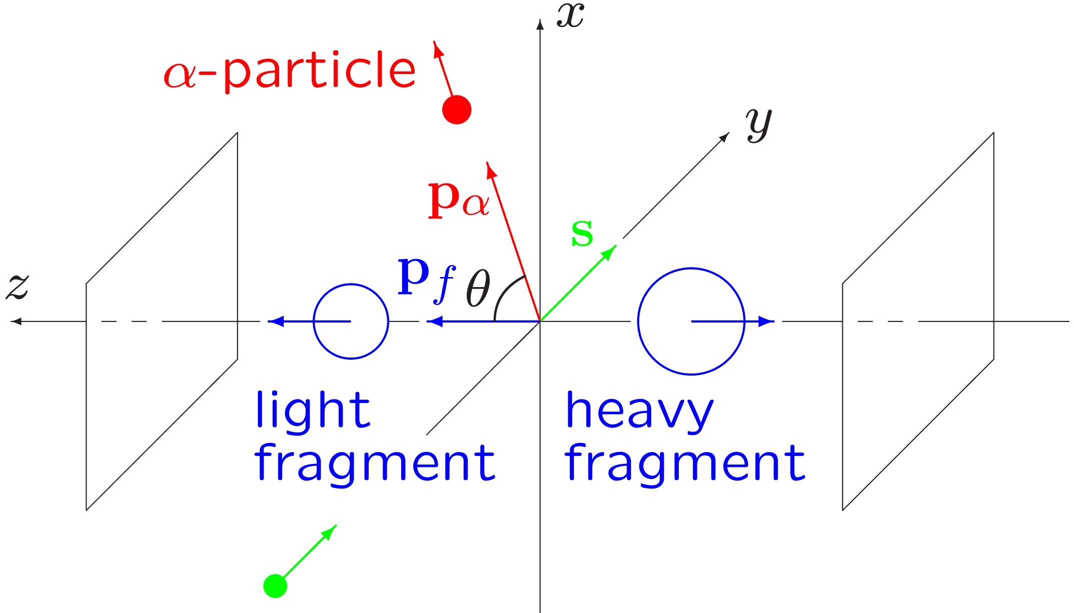
3. It would be interesting to find a more simple three-bode system with Coulomb repulsion to test this hypothesis.



s-wave neutron + nucleus (spin I) $\Rightarrow$ compound nucleus $J = I \pm \frac{1}{2}$

Generally:

$$\frac{d\sigma}{d\Omega_f d\Omega_\alpha} = \underbrace{\frac{d\sigma}{d\Omega_f d\Omega_\alpha}}_{J=I-1/2} + \underbrace{\frac{d\sigma}{d\Omega_f d\Omega_\alpha}}_{J=I+1/2} + \underbrace{\frac{d\sigma}{d\Omega_f d\Omega_\alpha}}_{J=I\pm 1/2,\, J'=I\mp 1/2}$$



s-wave neutron, $p_1(s)$ — neutron polarization

Polarization of fissioning compound nucleus with spin $J = I \pm \frac{1}{2}$:

$$p_1(J) = \begin{cases} -\frac{1}{3} p_1(s), & J = I - \frac{1}{2} \\ \frac{2I+3}{3(2I+1)} p_1(s), & J = I + \frac{1}{2}. \end{cases}$$