

T-shaped spin filter with a ring resonator

A.A. Kiselev and K.W. Kim

*Department of Electrical and Computer Engineering,
North Carolina State University, Raleigh, NC 27695-7911*

A planar ballistic structure is constructed to be highly effective in filtering electron spin from unpolarized source into two output channels with the opposite and practically pure spin polarizations. The operability of the proposed device relies on the peculiar spin-dependent transmission properties of the T-shaped connector in the presence of the Rashba spin-orbit interaction and difference in the dynamic phase gains on two alternative paths through upper and lower branches for even and odd eigenmodes in the ring resonator.

Idea 1

- In spintronic* devices one needs to manipulate spin
- Conventional approach --- by external magnetic field
 - micromagnets, ferromagnetic films, additional extensive circuitry, external magnets :-)
- Possible alternative --- *intrinsic effect* provided by spin-orbit (SO) interaction.** SO interaction *by definition* couples spin and orbit degrees of freedom

*) G. A. Prinz, Physics Today **48(4)**, 58 (1995); Science **282**, 1660 (1998).

***) S. Datta and B. Das, Appl. Phys. Lett. **56**, 665 (1990); Bulgakov, K. N. Pichugin, A. F. Sadreev, P. Strela, and P. Seba, Phys. Rev. Lett. **83**, 376 (1999); A.A. Kiselev and K.W. Kim, Appl. Phys. Lett. **78**, 775 (2001).

Idea 2

- Due to typically large difference in energy scales for spin and orbital motion, it is common to consider influence of SO term only on the spin coordinate (spin precession in the effective magnetic field).
- **Spin cannot influence electron trajectory**
- For any initial spin orientation, by the end of trajectory each spin will rotate by the same total angle
- Isotropic distribution of spins will convert into isotropic distribution.

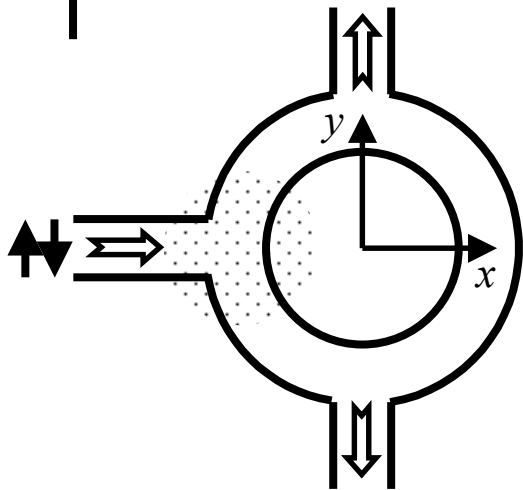
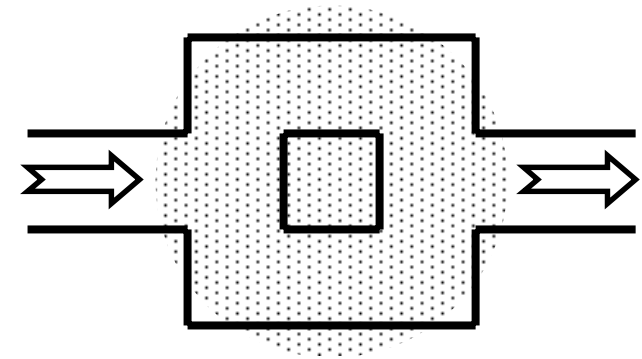
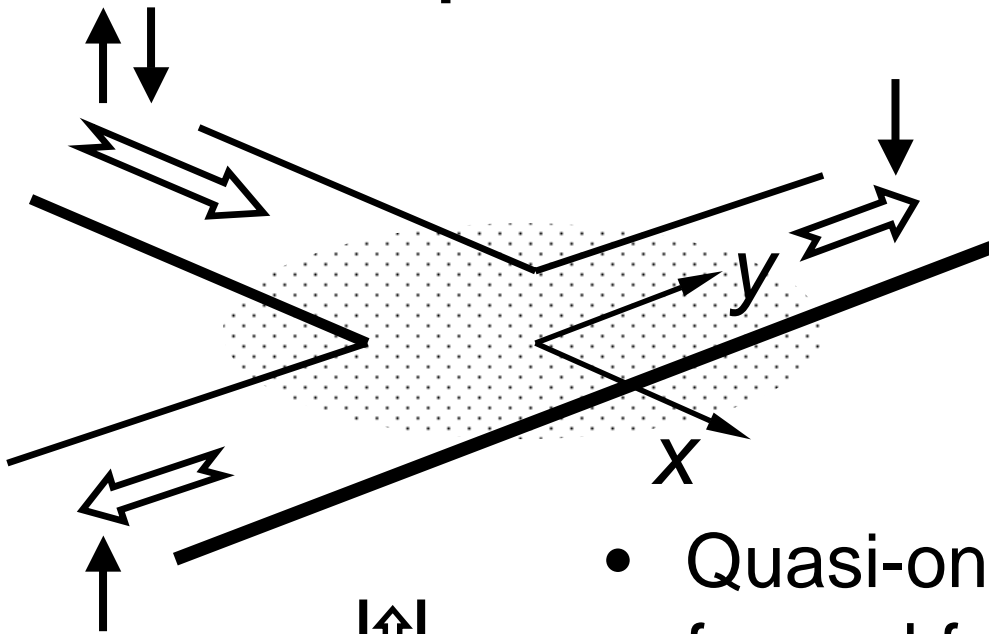
Idea 3

- *Reciprocal effect* can be made important in the vicinity of resonances where relevant orbital energy scale is *drastically* reduced up to the resonance width
- **Completely different trajectories for different spin orientations**
- Initial isotropic distribution of spins can be split into two or more with $\langle S \rangle \neq 0$. One can achieve spin filtering

Outline

- 2D ballistic structures for spintronics
- 2D electron Hamiltonian
- Scattering matrix and its symmetry properties
- Results for symmetric T-shaped structure
- T-shaped filter with a ring resonator
- Conclusion

T-shaped 2D structure and others...



- Quasi-one dimensional channels formed from the two-dimensional electron gas (2DEG) using, e.g., electrostatic split-gate technique
- Special control electrode(s) are located over/under the structure (back and front gates) to manipulate SO interaction

Hamiltonian and other formulae

- 2D electron Hamiltonian (including spin part)

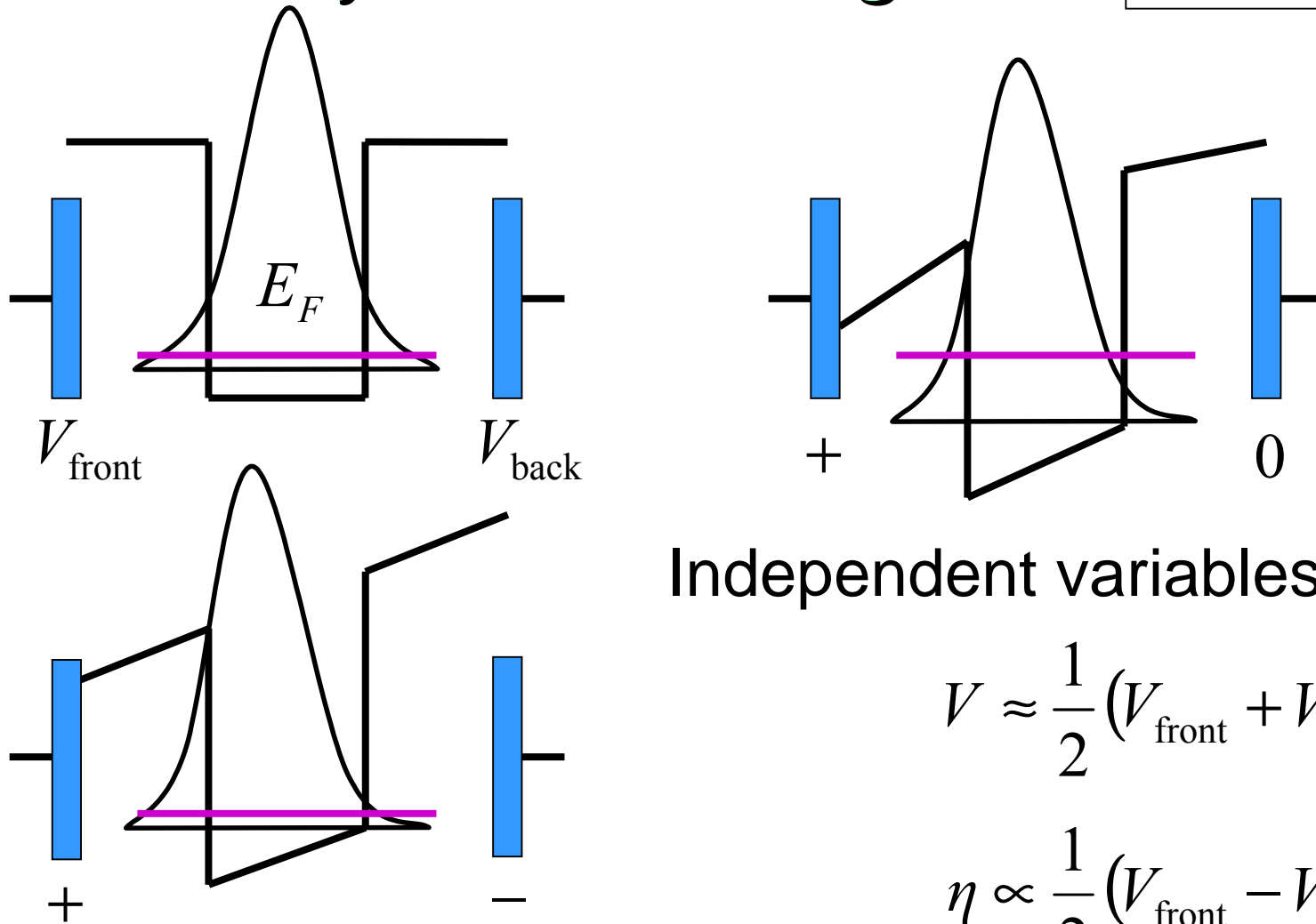
$$\hat{H} = \frac{\hbar^2 k^2}{2m} + \left\{ \eta(x, y) (\hat{\sigma}_x k_y - \hat{\sigma}_y k_x) \right\}$$

- Channels are formed by hard walls (with boundary conditions $\hat{u}_s \equiv 0$) or alternatively can be defined by the potential profile $V(x, y)$ (soft walls)
- The third dimension (i.e. z coordinate) is quantized.
- η reflects strength of the structure- or bulk-asymmetry-induced spin-orbit (SO) interaction*

*) Yu. A. Bychkov and E. I. Rashba, Sov. Phys. JETP Lett. **39**, 78 (1984);
G. Lommer, F. Malcher, and U. Rössler, Phys. Rev. B **32**, 6965 (1985).

Manipulation of SO term by front/back gates

$$\eta \propto \langle F \rangle$$



Independent variables:

$$V \approx \frac{1}{2} (V_{\text{front}} + V_{\text{back}})$$

$$\eta \propto \frac{1}{2} (V_{\text{front}} - V_{\text{back}})$$

D. Grundler, Phys. Rev. Lett. **84**, 6074 (2000).

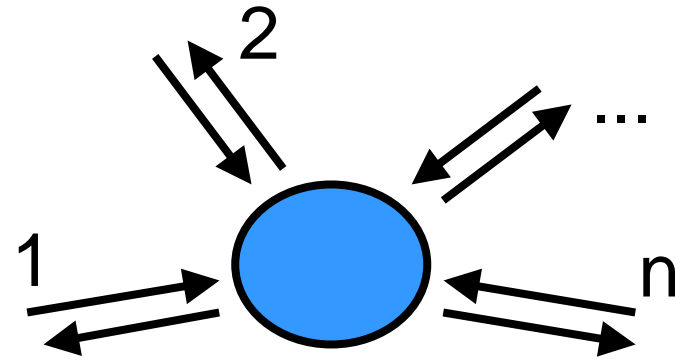
"T-shaped spin filter with a ring resonator"

Scattering matrix

- Definition:

$$\mathbf{U}_{\text{out}} = \mathbf{S}\mathbf{U}_{\text{in}}$$

$$\mathbf{S} = \begin{pmatrix} r_{11} & t_{12} & \cdots & t_{1n} \\ t_{21} & r_{22} & \cdots & t_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ t_{n1} & t_{n2} & \cdots & r_{nn} \end{pmatrix}$$



- Spinless particle: r_{ii} , t_{ij} are scalars
- Electron with spin: r_{ii} , t_{ij} are 2x2 matrices

$$\hat{x}_{ij} = x_{ij,1} \hat{1} + i \sum_{\alpha} x_{ij,\alpha} \hat{\sigma}_{\alpha}$$

Pure and partially polarized flux

- State in channel with 100% polarization $\hat{u} = \begin{pmatrix} u_{\uparrow} \\ u_{\downarrow} \end{pmatrix}$
- Elementary flux $F \propto \hat{u}^+ \hat{u}$, polarization \mathbf{P} : $P_{\alpha} F \propto \hat{u}^+ \hat{\sigma}_{\alpha} \hat{u}$
- For the arbitrary \hat{u} polarization $|\mathbf{P}| = 1$
- Partially polarized fluxes can be mimicked by a number of independent elementary fluxes \hat{u}_q

$$F = \sum_q F_q \quad \mathbf{P}F = \sum_q \mathbf{P}_q F_q$$

Unpolarized flux

- Use, for example, two elementary fluxes

$$\hat{u}_2 = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \quad \hat{u}_1 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

- If that is pumped into channel i , for flux, transmitted into channel j

$$F \propto |t_{ij,1}|^2 + |t_{ij,x}|^2 + |t_{ij,y}|^2 + |t_{ij,z}|^2$$

$$P_x F \propto 2 \operatorname{Im}(t_{ij,1} t_{ij,x}^* + t_{ij,y}^* t_{ij,z}), \quad \text{etc.}$$

Scattering matrix symmetry relations

- Flux conservation $F \propto \mathbf{U}^+\mathbf{U} \rightarrow \mathbf{S}^+\mathbf{S} = \mathbf{1}$

- Time-reversal operator $\hat{T} = -i\hat{\sigma}_y K$

$$\hat{\sigma}_y \mathbf{S}^* \hat{\sigma}_y \mathbf{S} = \mathbf{1} \qquad \hat{\sigma}_y \mathbf{S}^* \hat{\sigma}_y = \mathbf{S}^+$$

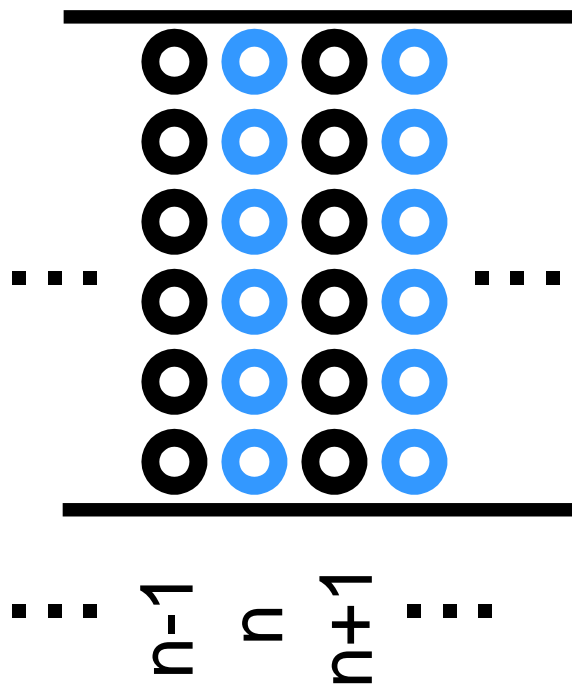
$$r_{ii,\alpha} \equiv 0, \quad t_{ij,1} \equiv t_{ji,1}, \quad t_{ij,\alpha} \equiv -t_{ji,\alpha}$$

- In particular case of *symmetric* ($y \leftrightarrow -y$) structure, there is an additional element $-i\hat{\sigma}_y S_y$

$$\hat{\sigma}_y S_y(\mathbf{S}) \hat{\sigma}_y = \mathbf{S} \quad S_y(\mathbf{S}): \text{permutation } (i, j, \dots) \leftrightarrow (k, l, \dots)$$

$$r_{ii,1} \equiv r_{kk,1}, \quad t_{ij,1} \equiv t_{kl,1}, \quad t_{ij,x} \equiv -t_{kl,x}, \quad t_{ij,y} \equiv t_{kl,y}, \quad t_{ij,z} \equiv -t_{kl,z}$$

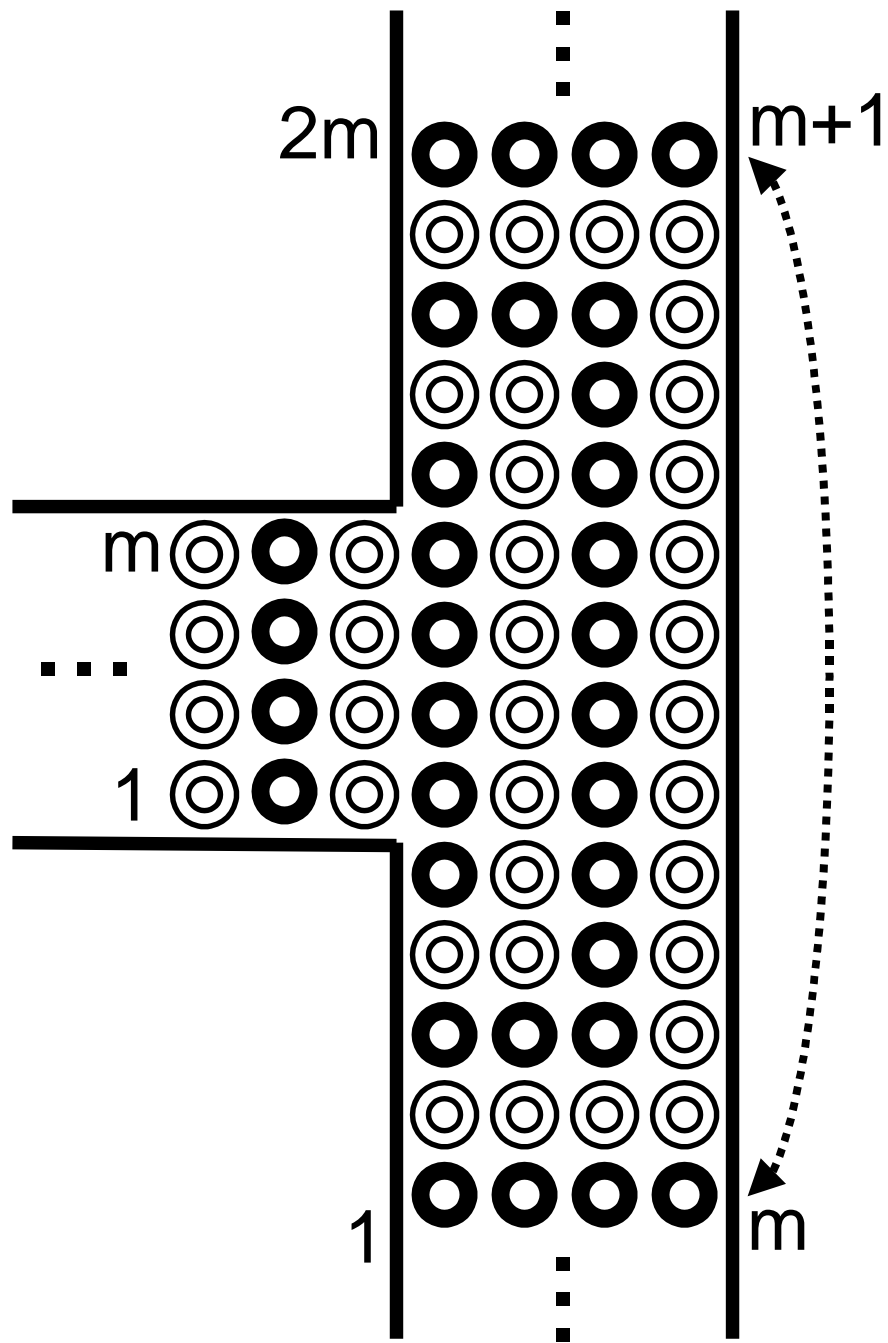
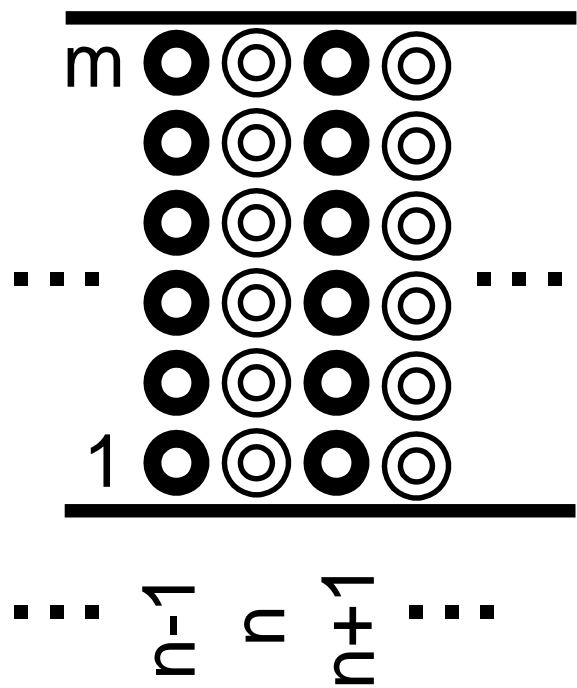
Numerical solution



- The problem is mapped to the mesh
- Schrödinger equation is converted to finite-difference equations
- “Columns” of points are formed
- Coupling of columns is expressed via transfer matrices
- Transfer-matrix approach is numerically stabilized by the recursion* (or it can be recursive Green’s function method**)

*) T. Usuki, M. Saito, M. Takatsu, R. A. Kiehl, and N. Yokoyama, Phys. Rev. B **52**, 8244 (1995).

***) T. Ando, Phys. Rev. B **44**, 8017 (1991).



"T-shaped spin filter with a ring resonator"

Real-life structure parameters

- Channel width, ring radius

$$w = 1000 \text{ \AA}, \quad r = 2000 \text{ \AA},$$

- Electron effective mass (InAs)

$$m = 0.023m_0$$

- Quantization energy

$$E_0 = 1.6 \text{ meV}$$

- SO term parameter

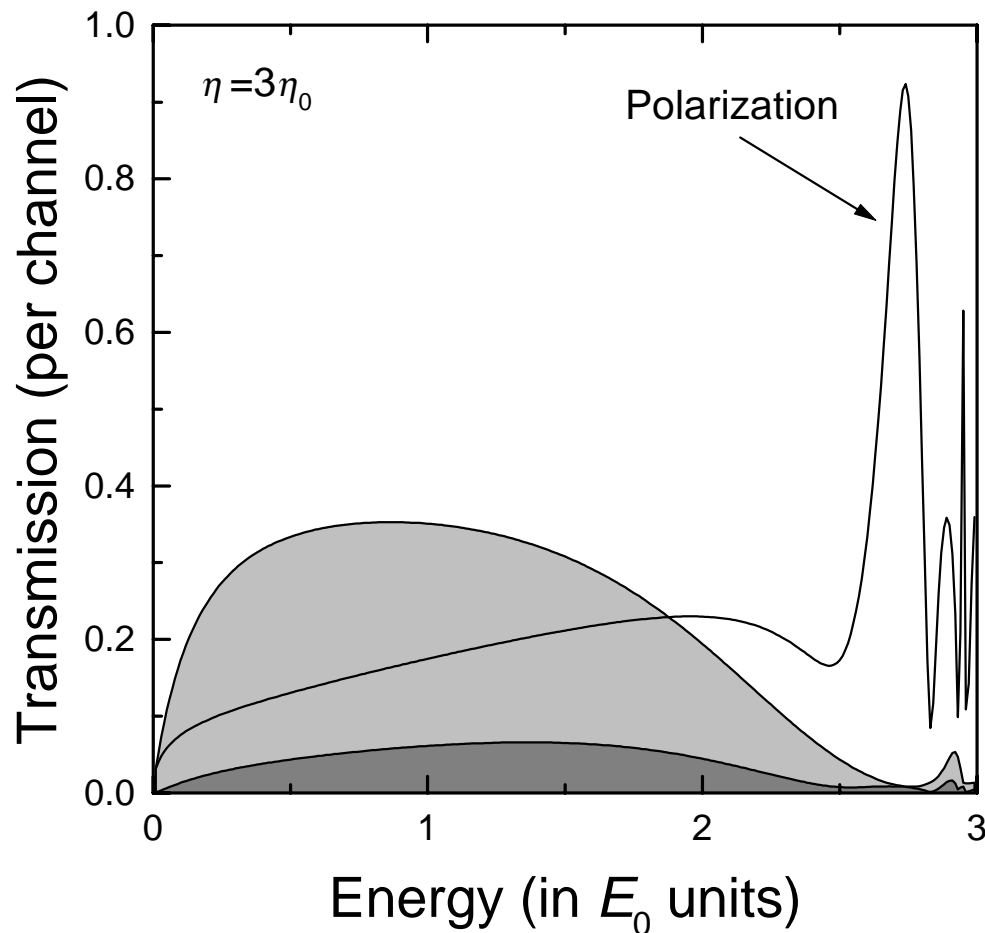
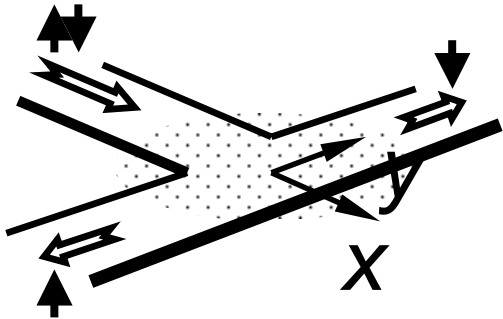
$$3\eta_0 = 180 \text{ meV} \cdot \text{\AA}$$

(that is equal to $0.11 \times E_0 w$)

- Electrode radius

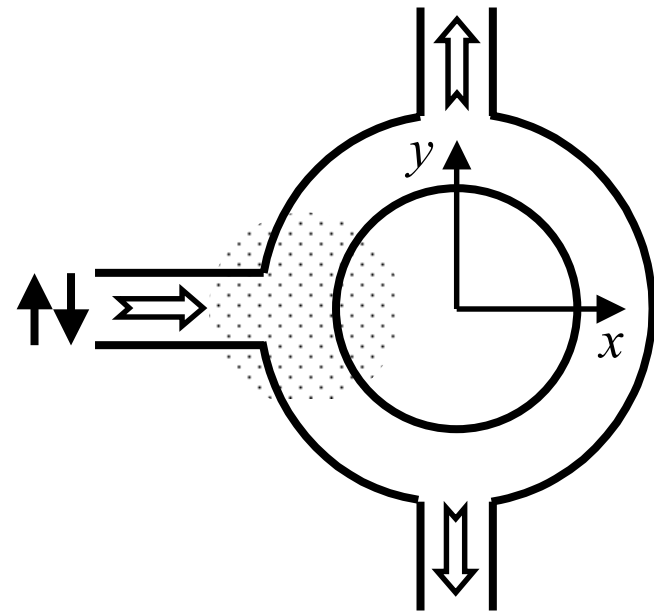
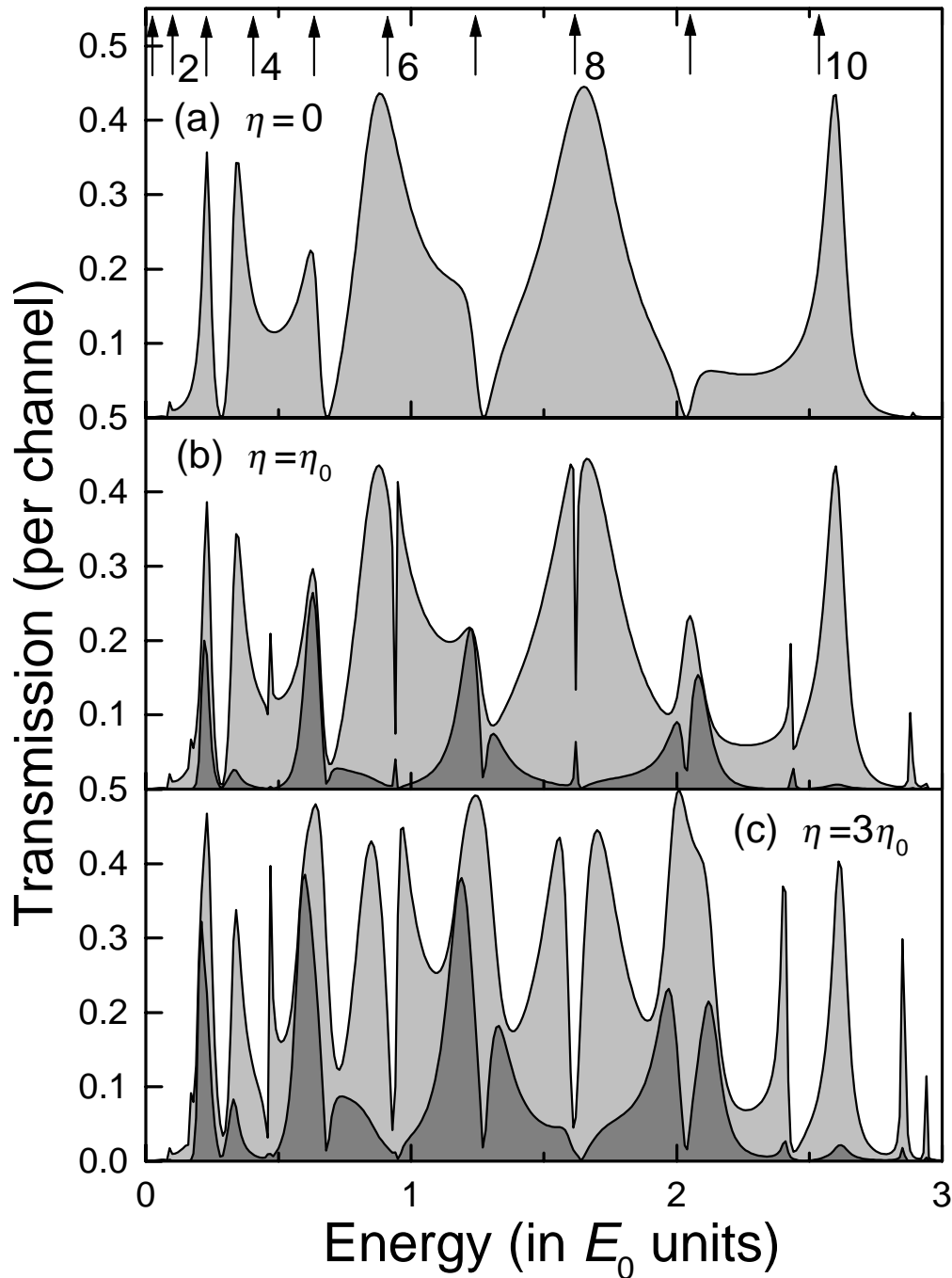
$$r_0 = 1000 \text{ \AA}$$

T-shaped filter: transmitted flux and its polarization



- Strong-coupling transmission regime in a broad energy interval
- Polarized flux is less than 6% of the incident flux
- Polarization can reach 100% quasi-localized states (fine structure)

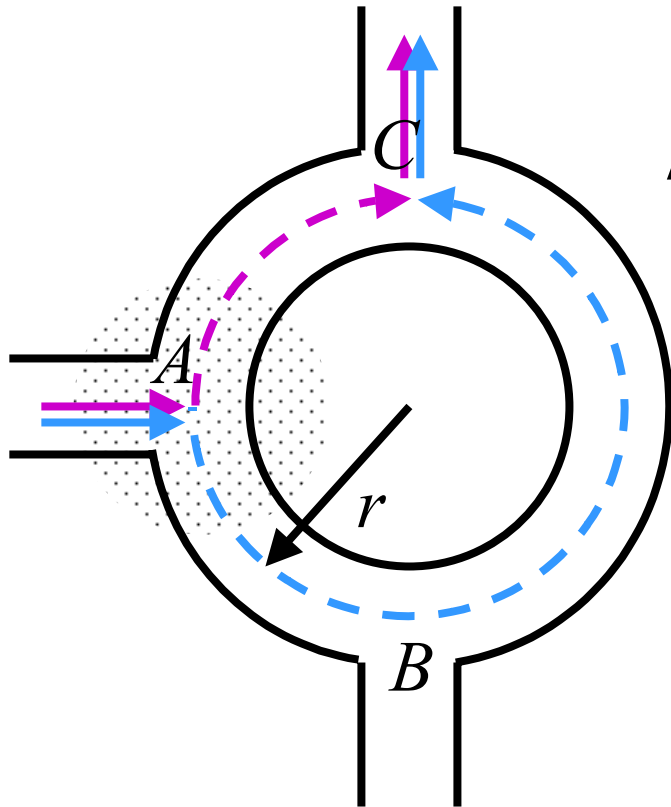
Modified structure: added ring resonator



We have achieved simultaneously high transmission and high spin polarization of the transmitted flux.

"T-shaped spin filter with a ring resonator"

Ring eigenmodes and interference



Exactly - via Bessel functions,
Approximately ($w \ll L = 2\pi r$):

$$E_{r,l} = \frac{\hbar^2 k_l^2}{2m} \quad k_l = \frac{2\pi l}{L} = \frac{l}{r} \quad l \text{ is integer}$$

($E_{r,l}$ counted from
quantization energy E_0)

$$\varphi_{ABC} - \varphi_{AC} = k_l L / 2 = \pi l$$

$$\Delta\varphi_{\text{T-shape}} = 0 \text{ for } t_{ij,1}, t_{ij,y}$$

$$\Delta\varphi_{\text{T-shape}} = \pi \text{ for } t_{ij,x}, t_{ij,z}$$

$\Delta\varphi_{\text{total}}$	$t_{ij,1}$	$t_{ij,x}$	$t_{ij,y}$	$t_{ij,z}$
odd modes	π	0	π	0
even modes	0	π	0	π

"T-shaped spin filter with a ring resonator"

Conclusion

- It is possible to achieve high spin polarizations applying T-shaped spin filter with a ring resonator to the unpolarized electrons
- It is possible to have simultaneously high flux and high-quality spin filtering
- No need for very sharp energy distributions
- The same device will operate as directional multiplexer when applied to the polarized electrons
- Functional ballistic spin devices can be designed that are based on the *internal* SO effect, modulated by control electrodes