IWNDT
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Spin-isospin effects in intermediate-energy heavy-ion collisions

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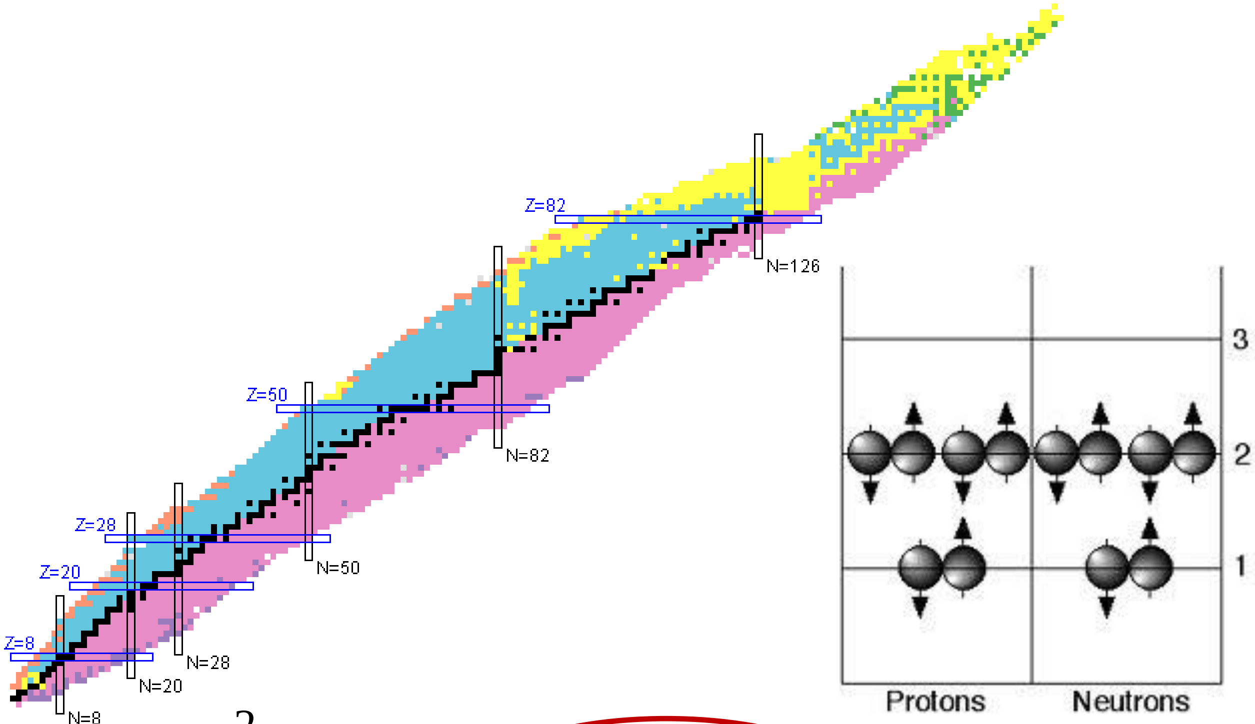
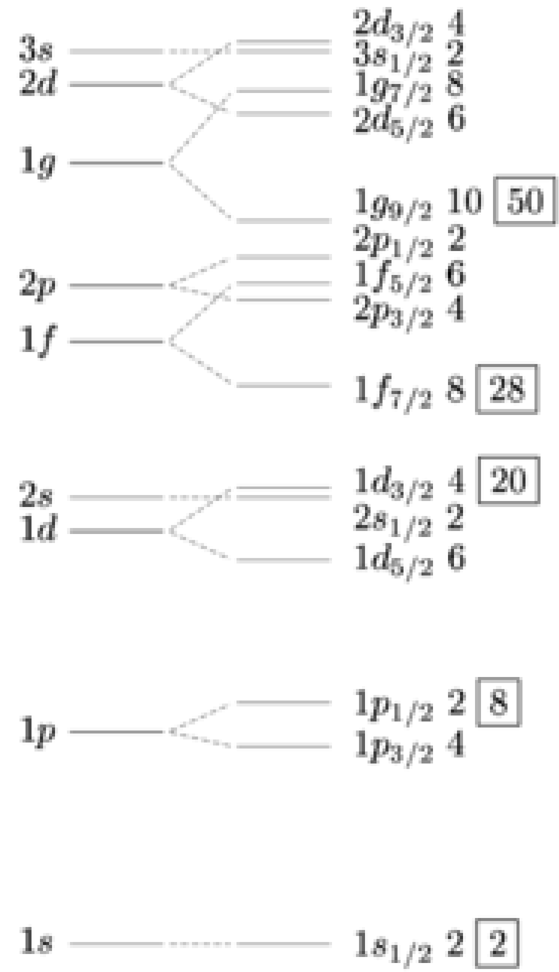
Outline

- Introduction: spin-orbit interaction
- Introduce spin-orbit interaction
  to IBUU transport model (SIBUU)
- Results and discussions
- Conclusion and outlook

Introduction





$$h_q = \frac{p^2}{2m} + U_q + \vec{W}_q \cdot (\vec{p} \times \vec{\sigma}), (q = n, p)$$

Schrödinger equation: $h_q \varphi_q = e_q \varphi_q$

The spin-orbit potential $\vec{W}_q \cdot (\vec{p} \times \vec{\sigma})$

helps to explain the magic number and shell structure.

An important component of nuclear interaction!

- Skyrme-Hartree-Fock model

$$V_{so} = iW_0(\vec{\sigma}_1 + \vec{\sigma}_2) \cdot \vec{k} \times \delta(\vec{r}_1 - \vec{r}_2)\vec{k}'$$

$$\Rightarrow \quad \vec{W}_q = \frac{W_0}{2}\left(\nabla\rho + \nabla\rho_q\right)$$

- Relativistic mean field model

Dirac equation

Non-relativistic expansion

$$\Rightarrow \quad \vec{W}_q = \frac{C}{(2m - C\rho)^2}\nabla\rho, C = \frac{g_\sigma^2}{m_\sigma^2} + \frac{g_\omega^2}{m_\omega^2}$$

P. G. Reinhard and H. Flocard, Nucl. Phys. A, 1995

Generally $\vec{W}_q = W_0\left(\frac{\rho}{\rho_0}\right)^\gamma\left(a\nabla\rho_q + b\nabla\rho_{q'}\right) \qquad (q \neq q')$

density dependence

isospin dependence

W_0= 80 ~ 150 MeVfm^5, γ, a, and b still under debate

The spin-orbit interaction may affect

1) Properties of drip-line nuclei

G. A. Lalazissis, *et al.*, Phys. Rev. Lett., 1998

2) Astrophysical r-process

B. Chen, *et al.*, Phys. Lett. B, 1995

3) Location of SHE

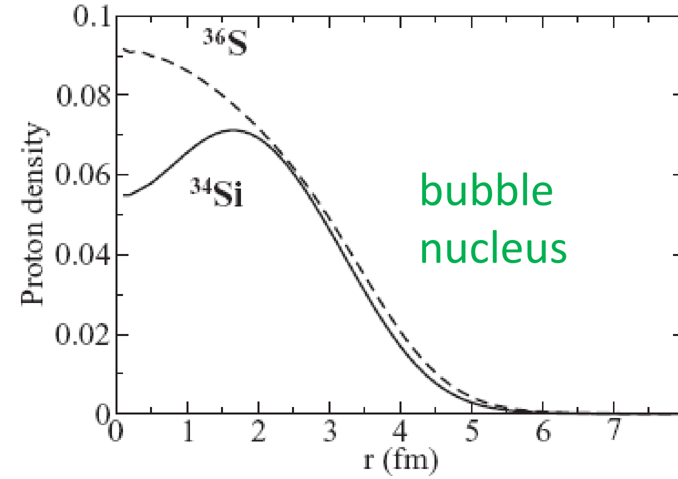
M. Bender, *et al.*, Phys. Rev. C, 1999

M. Morjean, *et al.*, Phys. Rev. Lett., 2008

4) …

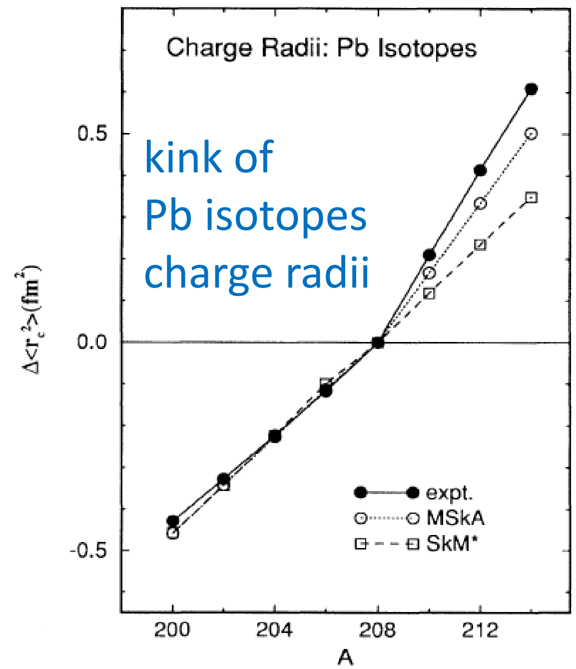
A hot topic in the studies of nuclear structure!

Density dependence



M. Grasso, *et al.*, Phys. Rev. C, 2009

Isospin dependence

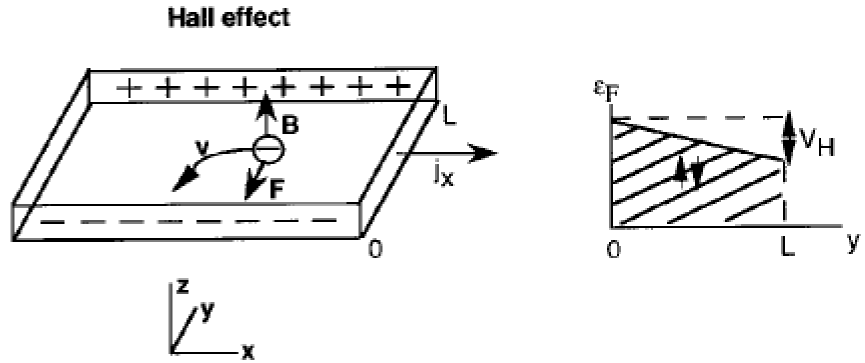


M. M. Sharma, *et al.*, Phys. Rev. Lett., 1995

- **Hall effect**

  Lorentz force

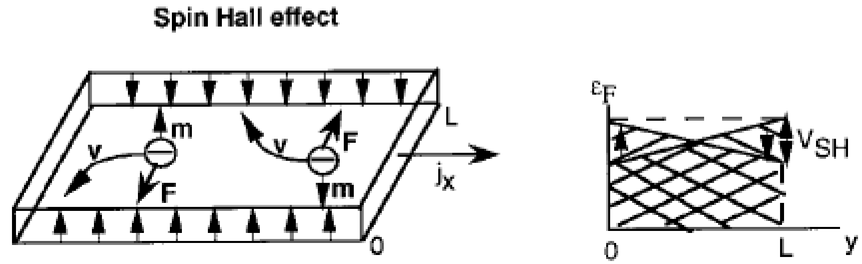
  $$\vec{F} = q\vec{v} \times \vec{B}$$



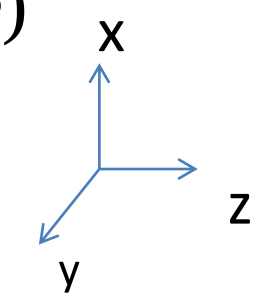
- **Spin Hall effect**

  Spin-orbit potential

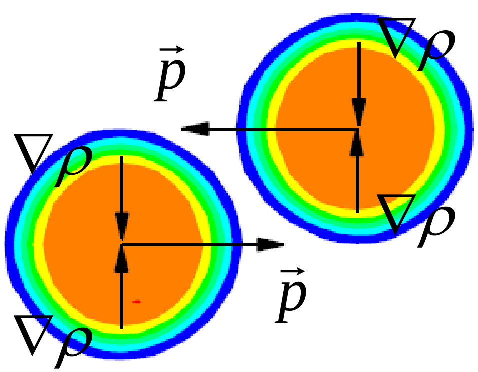
  $$U \sim -\vec{\sigma} \cdot \vec{L} \qquad \vec{\sigma} // \vec{L}$$

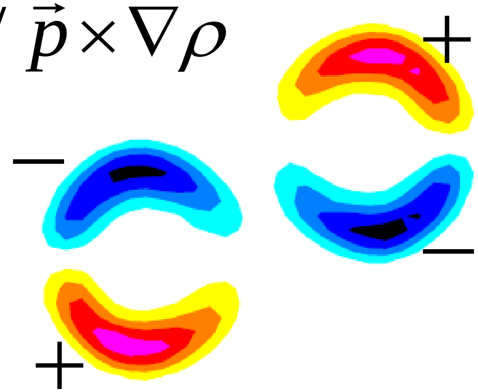


$$U_q^{so} = \vec{W}_q \cdot (\vec{p} \times \vec{\sigma}) = -\vec{\sigma} \cdot (\vec{p} \times \vec{W}_q) \sim -\vec{\sigma} \cdot (\vec{p} \times \nabla\rho)$$



$$\vec{\sigma} // \vec{p} \times \nabla\rho$$





Spin up +y

Spin down -y

density distribution

spin distribution

"Spurious" spin polarization!

Wait … We have time-odd terms

$$V_{so} = iW_0(\vec{\sigma}_1 + \vec{\sigma}_2) \cdot \vec{k} \times \delta(\vec{r}_1 - \vec{r}_2)\vec{k}'$$

Hartree-Fock ⟶

$$h_q = \frac{p^2}{2m} + U_q + U_q^s + U_q^{so}$$

$$U_q^s = -\frac{W_0}{2}[\nabla \cdot (\vec{J} + \vec{J}_q)] - \frac{W_0}{2}\vec{p} \cdot [\nabla \times (\vec{s} + \vec{s}_q)]$$

$$\boxed{- \frac{W_0}{2}\vec{\sigma} \cdot [\nabla \times (\vec{j} + \vec{j}_q)]},$$

Lorentz invariance

$$U_q^{so} = \boxed{\frac{W_0}{2}(\nabla\rho + \nabla\rho_q) \cdot (\vec{p} \times \vec{\sigma})},$$

ρ : number density
$\vec{J}$: spin-current density
} time-even

$\vec{s}$: spin density
$\vec{j}$: momentum density
} time-odd

U^{so} ⟹ $\vec{\sigma} \,//\, \vec{p} \times \nabla\rho$

U^{s} ⟹ $\vec{\sigma} \,//\, \nabla \times \vec{j}$

$$\nabla \times \vec{j} \sim \nabla \times (\vec{p}\rho) = \nabla\rho \times \vec{p}$$

Time-odd terms may cancel time-even terms!

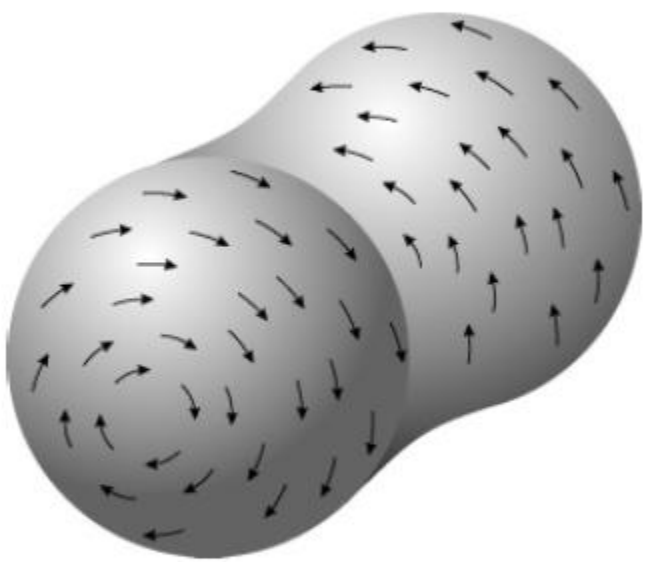
Spin effects at low and high energies

low energies (TDHF):

TABLE I. Thresholds for the inelastic scattering of $^{16}O + ^{16}O$ system.

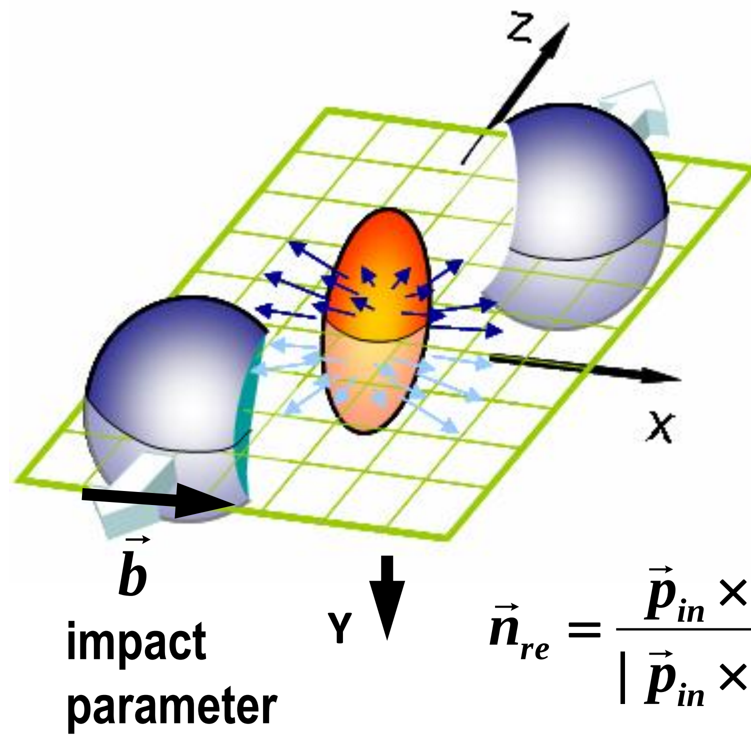
Force	Skyrme II (MeV)	Skyrme M* (MeV)
Spin orbit	68	70
No spin orbit	31	27

A. S. Umar *et al.*, Phys. Rev. Lett., 1986



J. A. Maruhn *et al.*, Phys. Rev. C, 2006

high energies:



$$\vec{n}_{re} = \frac{\vec{p}_{in} \times \vec{b}}{|\vec{p}_{in} \times \vec{b}|}$$

perpendicular to the reaction plane

Z. T. Liang and X. N. Wang,
Phys. Rev. Lett., 2005
Phys. Lett. B, 2005

Introduce spin-orbit interaction to IBUU

Generally
$$U_q^s = -\frac{W_0^\star(\rho)}{2}[\nabla\cdot(a\vec{J}_q + b\vec{J}_{q'})] - \frac{W_0^\star(\rho)}{2}\vec{p}\cdot[\nabla \times (a\vec{s}_q + b\vec{s}_{q'})] - \frac{W_0^\star(\rho)}{2}\vec{\sigma}\cdot[\nabla\times(a\vec{j}_q + b\vec{j}_{q'})],$$

$$W_0^\star(\rho) = W_0(\rho/\rho_0)^\gamma$$

$$U_q^{so} = \frac{W_0^\star(\rho)}{2}(a\nabla\rho_q + b\nabla\rho_{q'})\cdot(\vec{p}\times\vec{\sigma}).(q \neq q')$$

Equations of motion:

$$\frac{d\vec{r}}{dt} = \frac{\vec{p}}{m} + \frac{W_0^\star(\rho)}{2}\vec{\sigma}\times(a\nabla\rho_q + b\nabla\rho_{q'}) - \frac{W_0^\star(\rho)}{2}\nabla\times(a\vec{s}_q + b\vec{s}_{q'}),$$

$$\frac{d\vec{p}}{dt} = -\nabla U_q - \nabla U_q^s - \nabla U_q^{so},$$

$$\frac{d\vec{\sigma}}{dt} = W_0^\star(\rho)[(a\nabla\rho_q + b\nabla\rho_{q'})\times\vec{p}]\times\vec{\sigma} - W_0^\star(\rho)[\nabla\times(a\vec{j}_q + b\vec{j}_{q'})]\times\vec{\sigma}.$$

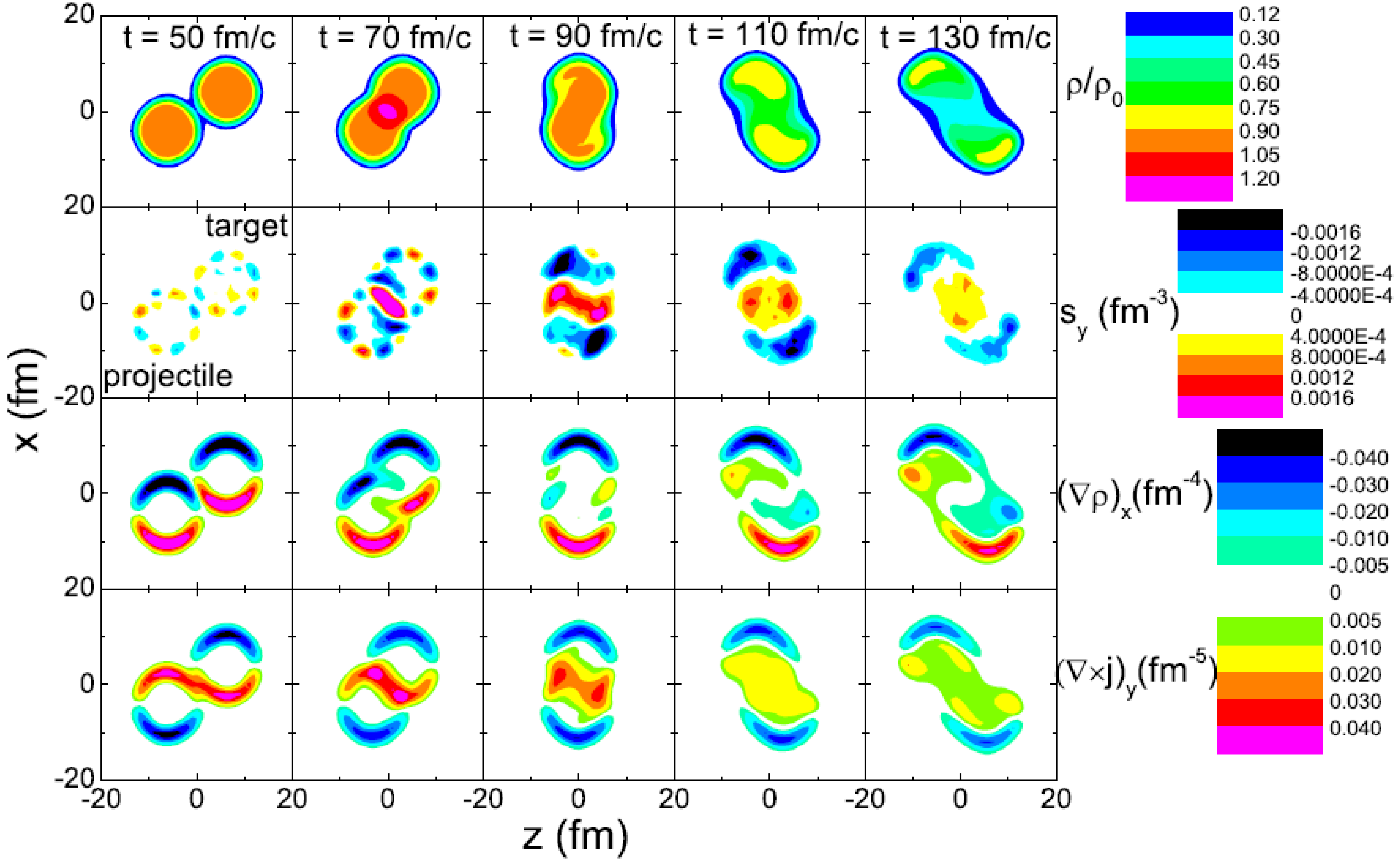
ρ, $\vec{J}$, $\vec{s}$, and $\vec{j}$ from test particle method

spin- and isospin-dependent Pauli blocking

Nucleon spin may flip after nucleon-nucleon scattering (randomized?)

Results and discussions

Au+Au@50MeV/A b = 8 fm W_0 = 150 MeVfm^5 γ = 0 a = 2 b = 1



Time-odd terms overwhelm time-even terms!

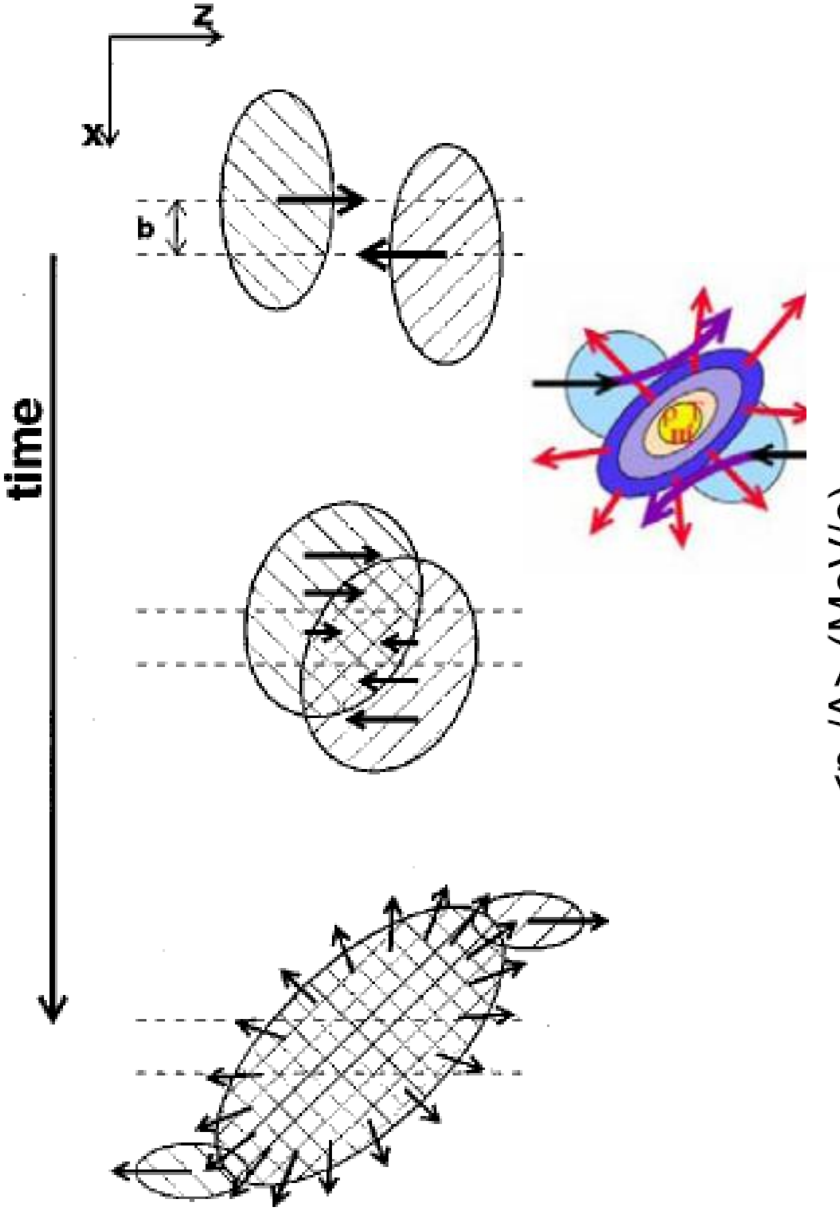
Transverse flow $\langle p_x \rangle \sim y$

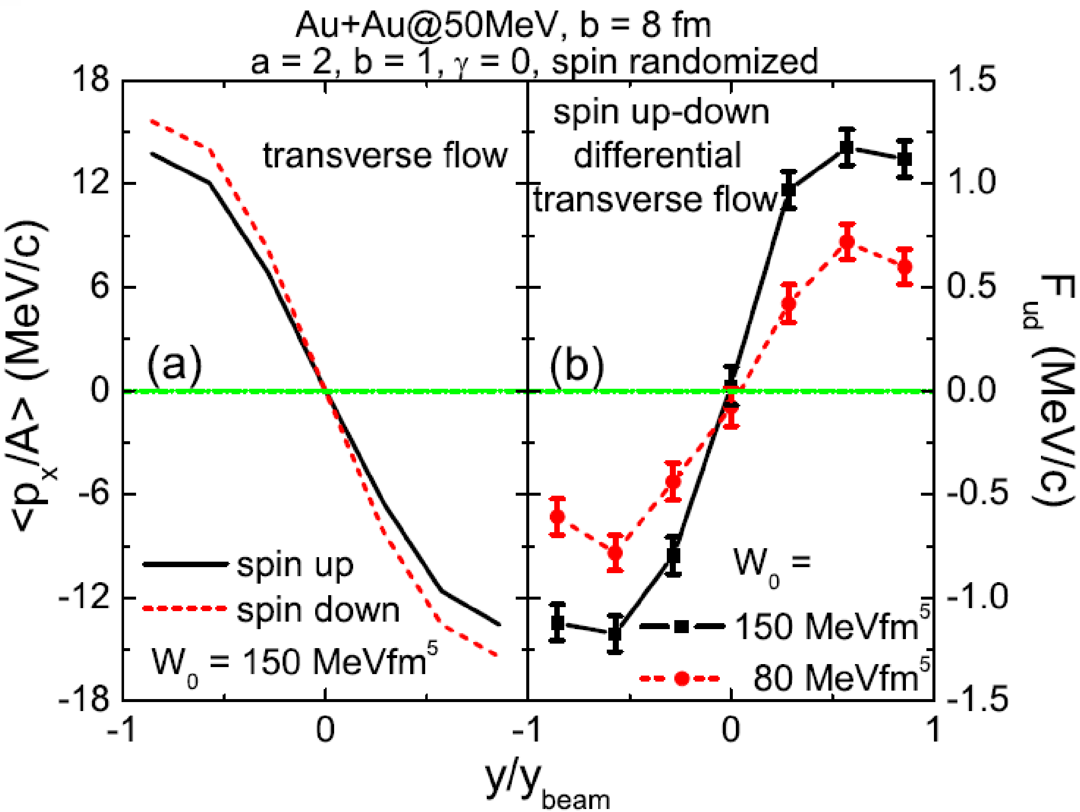
sensitive to nuclear interaction

Spin up-down differential transverse flow

$$F_{ud}(y) = \frac{1}{N(y)} \sum_{i=1}^{N(y)} \sigma_i (p_x)_i$$

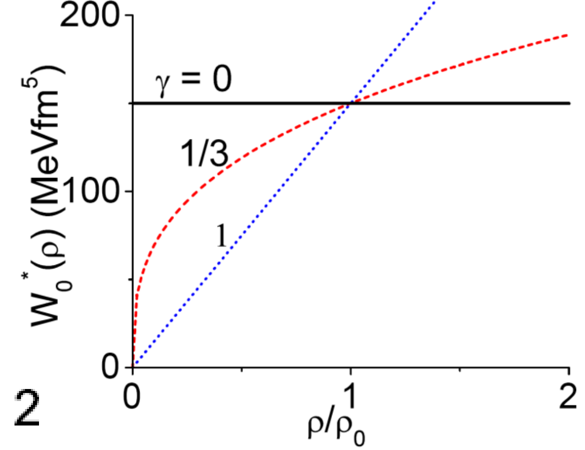
reflects different transverse flows of spin-up and spin-down nucleons

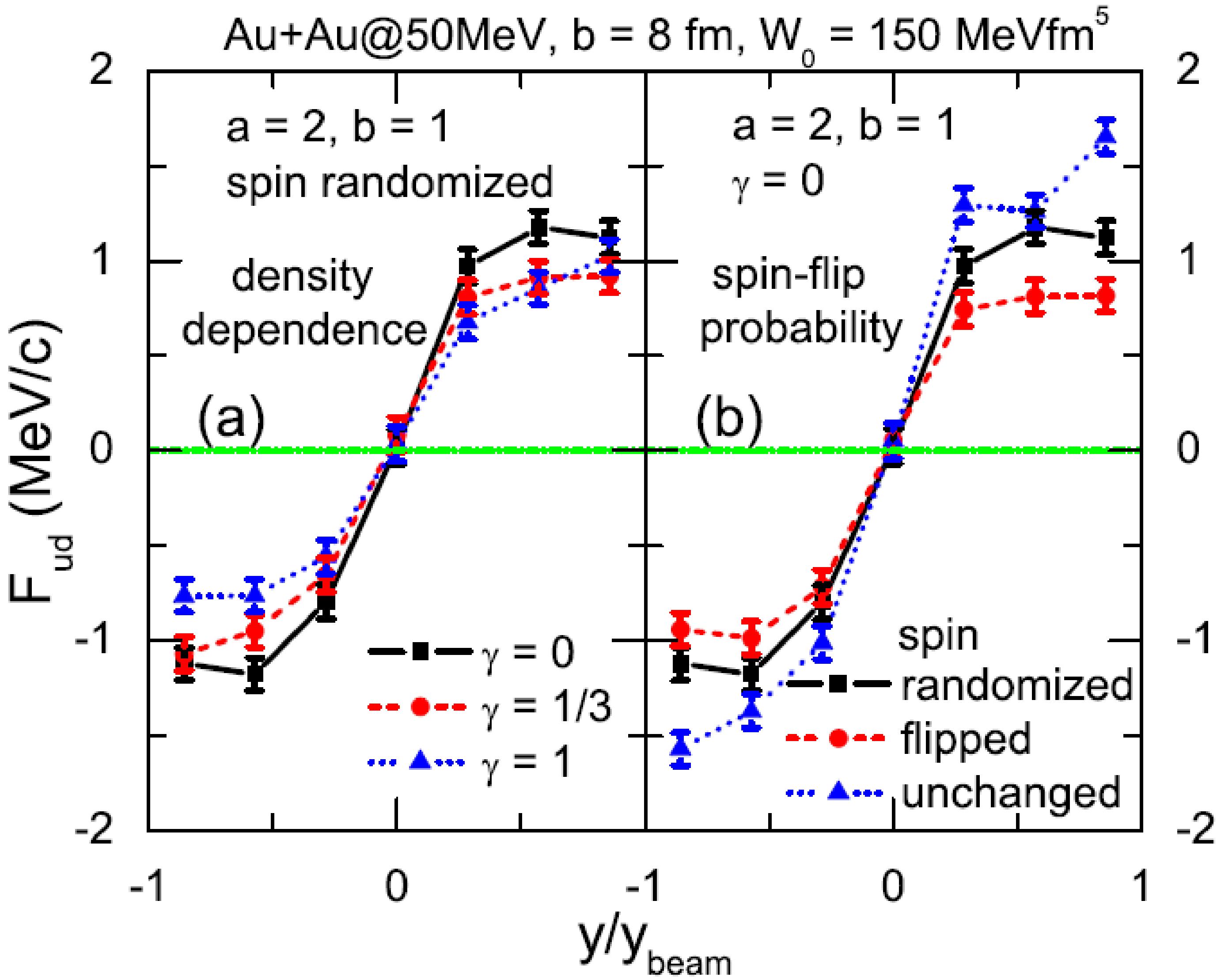




F_{ud} is sensitive to W_0, the strength of the spin-orbit interaction.

$$\frac{W_0}{2}\left(\frac{\rho}{\rho_0}\right)^{\gamma}\left(a\nabla\rho_q + b\nabla\rho_{q'}\right) + \ldots$$



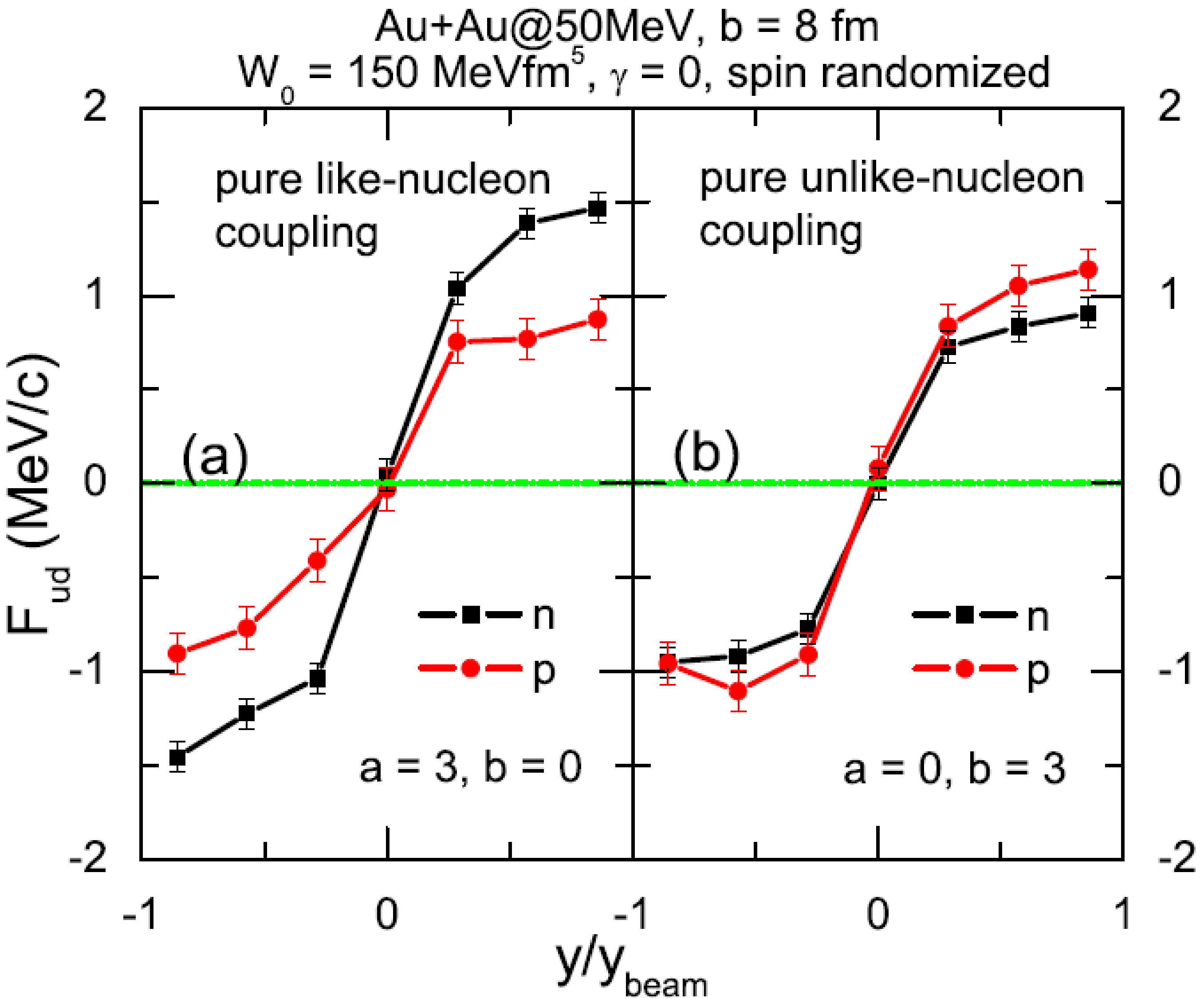


More sensitive to subsaturation spin-orbit interaction

F_{ud} decreases with increasing spin-flip probability

$$\frac{W_0}{2}\left(\frac{\rho}{\rho_0}\right)^{\gamma}\left(a\nabla\rho_q + b\nabla\rho_{q'}\right)+\ldots$$

A globally neutron-rich system



$$|\nabla\rho_n| > |\nabla\rho_p|$$

$$|\nabla\times\vec{j}_n| > |\nabla\times\vec{j}_p|$$

Relative strength of like and unlike coupling affects:

1) Relative F_{ud} for n and p

2) Total magnitude of F_{ud}

Conclusion and outlook

- Conclusion:
  - Introduce spin and spin-orbit interaction to a transport model for intermediate-energy heavy-ion collisions for the first time
  - Local spin polarization observed
  - Spin up-down differential flow is a sensitive probe for in-medium spin-orbit interaction

- Outlook:
  - Adjust mass, isospin asymmetry, impact parameter, and collision energy of the system in extensive studies
  - Introduce tensor force to heavy-ion collisions
  - Search for more spin-related observables
  - Model dependence: IQMD, RVUU, …

- Experiments
  - Spin polarization of projectile fragments (measured at RIKEN for 20 years!)
  - Analyzing power in pp and pA collisions at AGS or RHIC energy
  - Measurable at Time projection Chamber (TPC) or 4π detector (?)