QPT16, Oct. 26th, Guilin, 2025

同濟大學 TONGJI UNIVERSITY

Spin dynamics in intermediate-energy HIC

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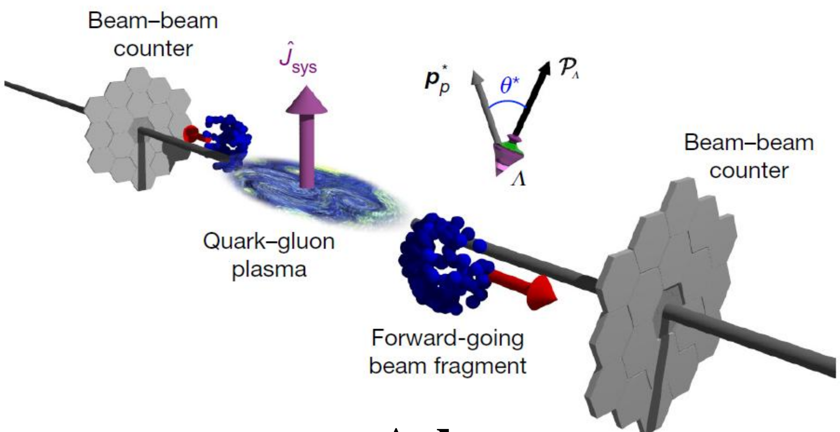
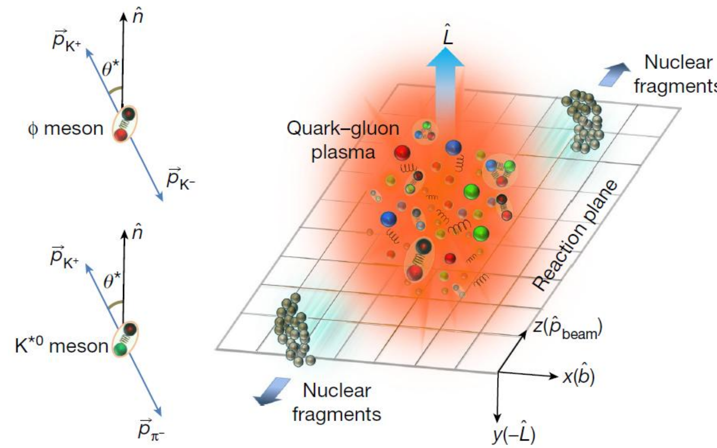
Collaborators： Bao-An Li, Rong-Jun Liu, Yin Xia, Yu-Gang Ma, Wen-Qing Shen

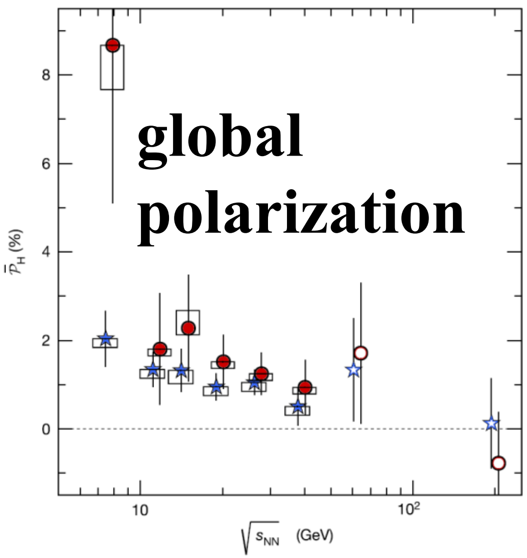
Probing properties of nuclear spin-orbit interaction with nucleon spin polarization in intermediate-energy heavy-ion collisions
J. Xu, Phys. Rev. C 111, L021602 (2025)
Spin polarization from nucleon-nucleon scatterings in intermediate-energy heavy-ion collisions
R.J. Liu, J. Xu*, Y.G. Ma, Phys. Lett. B 868, 139703 (2025)
Spin dynamics in intermediate-energy heavy-ion collisions with rigorous angular momentum conservation
R.J. Liu and J. Xu*, Phys. Rev. C 109, 014615 (2024)
Revisiting angular momentum conservation in transport simulations of intermediate energy heavy-ion collisions
R.J. Liu and J. Xu*, Universe 9, 36 (2023)
Nucleon spin polarization in intermediate-energy heavy-ion collisions
Y. Xia and J. Xu*, Phys. Lett. B 800, 135130 (2020)
Simulating spin dynamics with spin-dependent cross sections in heavy-ion collisions
Y. Xia, J. Xu*, B.A. Li, and W.Q. Shen Phys. Rev. C 96, 044618 (2017)
Equations of motion of test particles for solving the spin-dependent Boltzmann Vlasov equation
Y. Xia, J. Xu*, B.A. Li, and W.Q. Shen, Phys. Lett. B 759, 596 (2016)

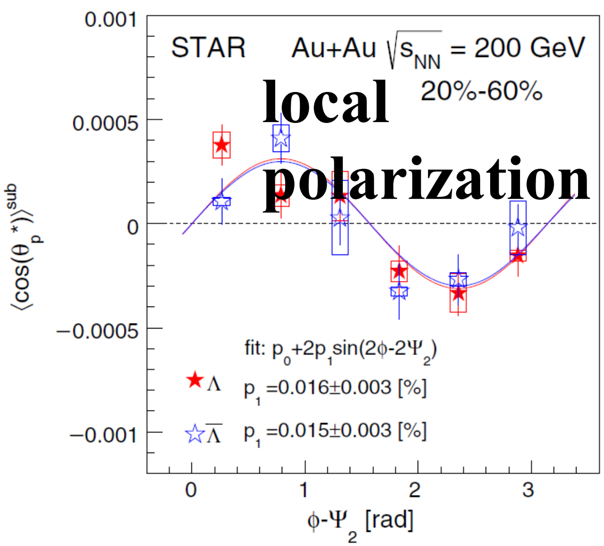
Spin polarization/alignment in relativstic HIC

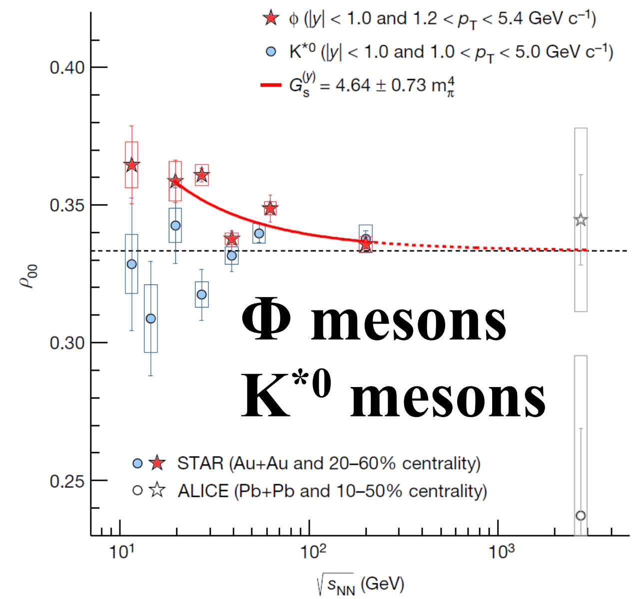




Λ hyperons







STAR Collaboration, Nature (2017); PRL (2019)

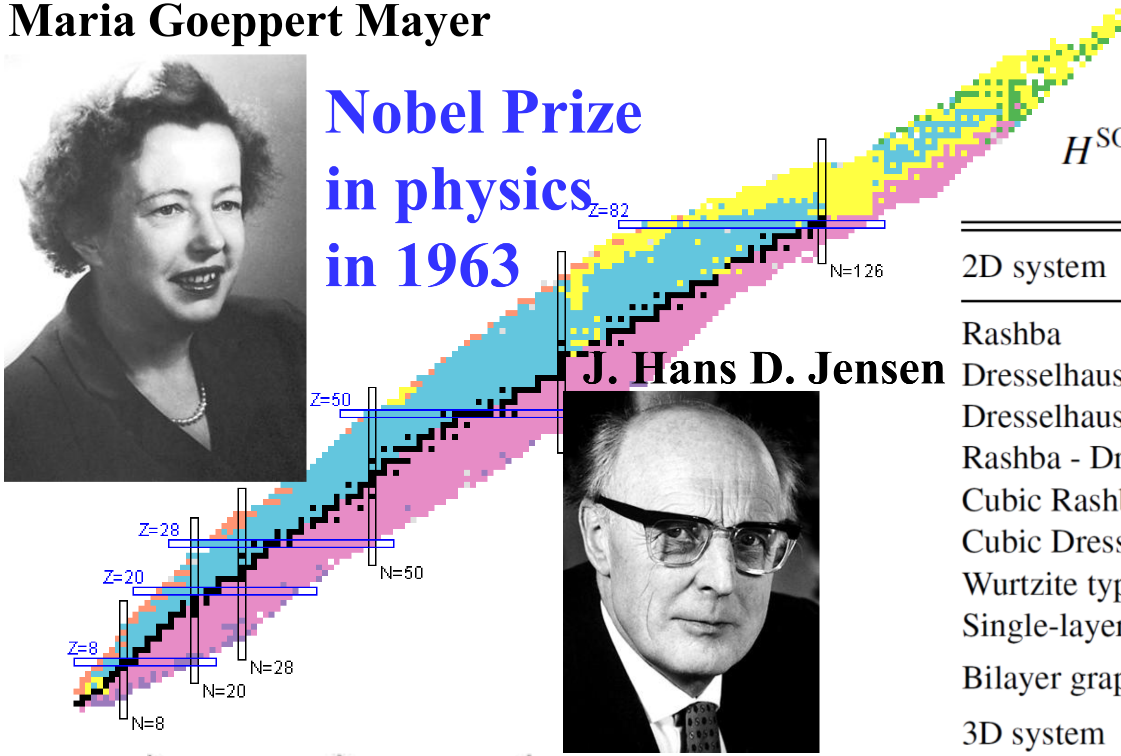
STAR Collaboration, Nature (2023)

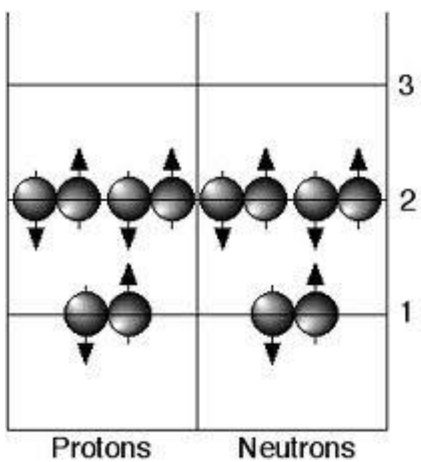
Spin-orbit coupling

Maria Goeppert Mayer

Nobel Prize in physics in 1963

J. Hans D. Jensen





$$\left(\overrightarrow{W_q} \times \vec{p}\right) \cdot \vec{\sigma}$$

spin-orbit coupling in different systems

$$H^{SO} = A(\vec{p})\sigma_x - B(\vec{p})\sigma_y + C(\vec{p})\sigma_z = \vec{b} \cdot \vec{\sigma}$$

2D system	A(p)	B(p)	C(p)
Rashba	$\beta_R p_y$	$\beta_R p_x$	
Dresselhaus [001]	$\beta_D p_x$	$\beta_D p_y$	
Dresselhaus [110]	βp_x	$-\beta p_x$	
Rashba - Dresselhaus	$\beta_R p_y - \beta_D p_x$	$\beta_R p_x - \beta_D p_y$	
Cubic Rashba (hole)	$i\frac{\beta_R}{2}(p_-^3 - p_+^3)$	$\frac{\beta_R}{2}(p_-^3 + p_+^3)$	
Cubic Dresselhaus	$\beta_D p_x p_y^2$	$\beta_D p_y p_x^2$	
Wurtzite type	$(\alpha + \beta p^2)p_y$	$(\alpha + \beta p^2)p_x$	
Single-layer graphene	$v p_x$	$-v p_y$	
Bilayer graphene	$\frac{p_-^2 + p_+^2}{4m_e}$	$\frac{p_-^2 - p_+^2}{4m_e i}$	
3D system	A(p)	B(p)	C(p)
Bulk Dresselhaus	$p_x(p_y^2 - p_z^2)$	$p_y(p_x^2 - p_z^2)$	$p_z(p_x^2 - p_y^2)$
Cooper pairs	Δ	0	$\frac{p^2}{2m} - \epsilon_F$
Extrinsic $\beta = \frac{i}{\hbar}\lambda^2 V(p)$	$q_y p_z - q_z p_y$	$q_z p_x - q_x p_z$	$q_x p_y - q_y p_x$
Neutrons in nuclei $\beta = i W_0(n_n + \frac{n_p}{2})$	$q_z p_y - q_y p_z$	$q_x p_z - q_z p_x$	$q_y p_x - q_x p_y$

K. Morawetz, PRB (2015)

- **Skyrme-Hartree-Fock model**

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

Hartree-Fock method →

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

- **Relativistic mean field model**

Dirac equation

Non-relativistic expansion →

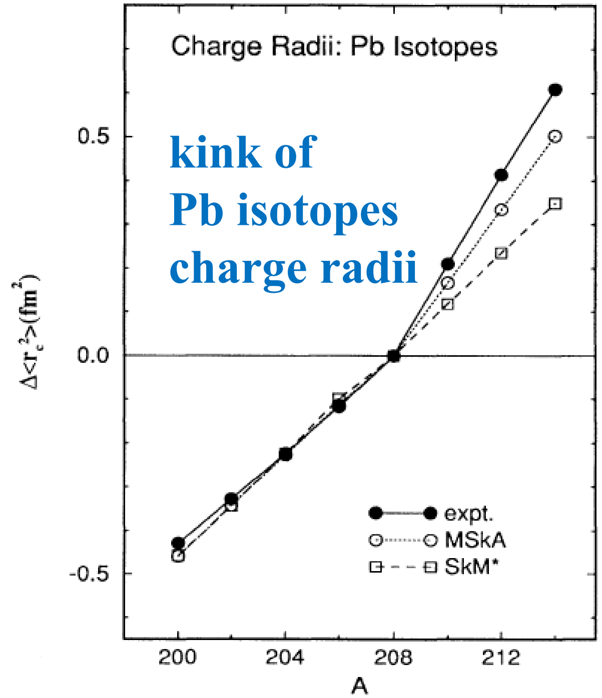
$$\vec{W}_q = \frac{C}{(2m - C\rho)^2}\nabla\rho, C = \frac{g_\sigma^2}{m_\sigma^2} + \frac{g_\omega^2}{m_\omega^2}$$

P.G. Reinhard and H. Flocard, NPA (1995)

the isospin dependence of the SO potential

$$\vec{W}_q = \frac{W_0}{2}(1+\chi_w)\nabla\rho_q + \frac{W_0}{2}\nabla\rho_{q'}.(q \neq q')$$

M.M. Sharma et al., PRL (1995)



the density dependence of the SO potential

$$v_{ij} = v_{ij}^0 + (i/\hbar^2) W_1 (\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_j) \cdot \mathbf{p}_{ij}$$
$$\times (\rho_{q_i} + \rho_{q_j})^\gamma \delta(\mathbf{r}_{ij}) \mathbf{p}_{ij}.$$

$$\vec{W}_q = \frac{W_0}{2}\nabla(\rho + \rho_q) + \frac{W_1}{2}[(\rho)^\gamma \nabla(\rho - \rho_q)$$
$$+ (2+\gamma)(2\rho_q)^\gamma \nabla\rho_q] + \frac{W_1}{4}\gamma\rho^{\gamma-1}(\rho - \rho_q)\nabla\rho$$

W_1 and γ fitted to reproduce the density dependence of the SO potential from the RMF model

Similar spin-orbit field in semi-infinite nuclear matter

J.M. Pearson and M. Farine, PRC (1994).

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

density dependence — **isospin dependence**

Confliction of PREXII and CREX

T.G. Yue, Z. Zhang, and L.W. Chen, arXiv: 2406.03844

W_0 = 80 ~ 150 MeVfm^5, α, β, and γ still under debate

T. Lesinski et al., PRC (2007); M. Zalewski et al., PRC (2008); M. Bender et al., PRC (2009)

Spin dynamics in low-energy reactions

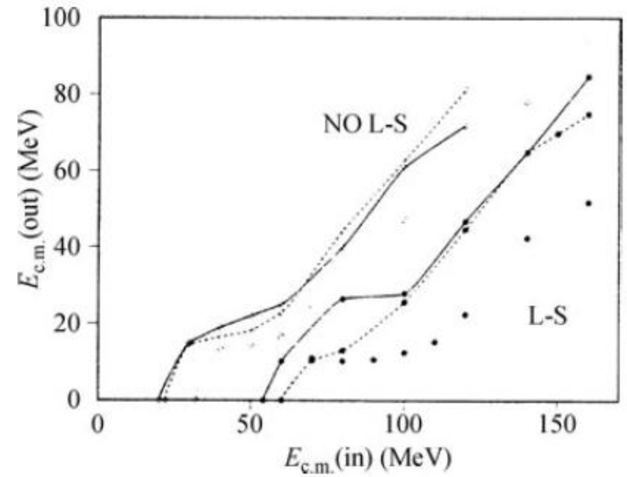
$^{16}O+^{16}O$ reactions from TDHF

fusion reaction threshold

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

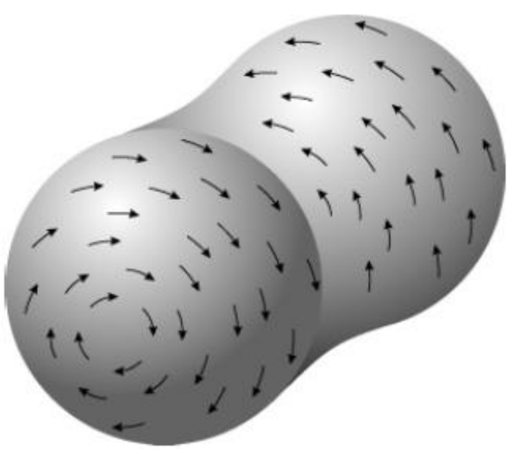
Force	Skyrme II (MeV)	Skyrme M* (MeV)
Spin orbit	68	70
No spin orbit	31	27

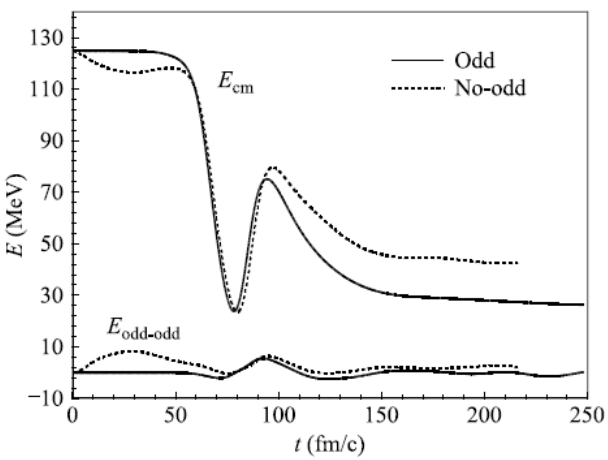
A.S. Umar *et al.*, PRL (1986)



P.G. Reinhard *et al.*, PRC (1988)

internal excitation (spin twist)





J.A. Maruhn *et al.*, PRC (2006)

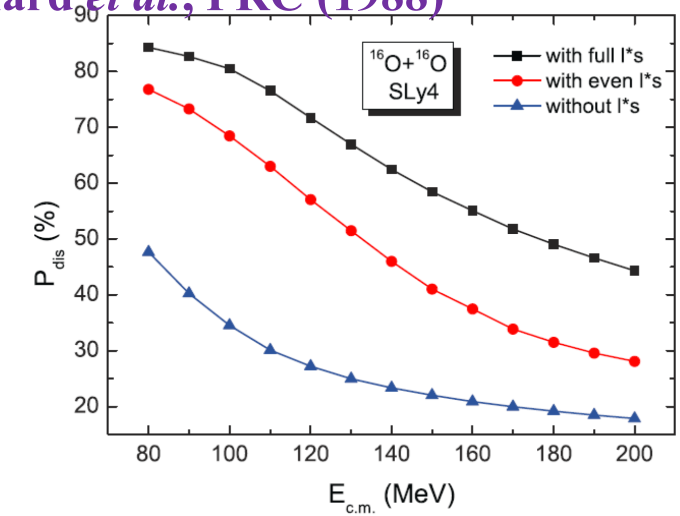


FIG. 2. (Color online) Percentage of energy dissipation as a function of center-of-mass energy for head-on collisions of $^{16}O + ^{16}O$ with parametrization SLy4. The black, red, and blue lines represent the TDHF calculations involving full l*s, time-even l*s, and no l*s force.

G.F. Dai, L. Guo, E.G. Zhao, and S.G. Zhou, PRC (2014)

Spin-dependent Boltzmann equation

$$\frac{\partial \hat{f}}{\partial t} + \frac{i}{\hbar}\left[\hat{\varepsilon}, \hat{f}\right] + \frac{1}{2}\left(\frac{\partial \hat{\varepsilon}}{\partial \vec{p}} \cdot \frac{\partial \hat{f}}{\partial \vec{r}} + \frac{\partial \hat{f}}{\partial \vec{r}} \cdot \frac{\partial \hat{\varepsilon}}{\partial \vec{p}}\right) - \frac{1}{2}\left(\frac{\partial \hat{\varepsilon}}{\partial \vec{r}} \cdot \frac{\partial \hat{f}}{\partial \vec{p}} + \frac{\partial \hat{f}}{\partial \vec{p}} \cdot \frac{\partial \hat{\varepsilon}}{\partial \vec{r}}\right) = I_c$$

H. Smith and H.H. Jensen, transport phenomena (Oxford University press, Oxford, 1989)

spin-particle energy $\hat{\varepsilon}(\vec{r}, \vec{p}) = \varepsilon(\vec{r}, \vec{p})\hat{I} + \vec{h}(\vec{r}, \vec{p}) \cdot \vec{\sigma},$

phase-space distribution function $\hat{f}(\vec{r}, \vec{p}) = f_0(\vec{r}, \vec{p})\hat{I} + \vec{g}(\vec{r}, \vec{p}) \cdot \vec{\sigma},$

spin-dependent Wigner function

$$f_{\sigma,\sigma'}(\vec{r}, \vec{p}, t) = \int d^3 s e^{-i\vec{p}\cdot\vec{s}/\hbar} \psi^*_{\sigma'}(\vec{r} - \frac{\vec{s}}{2}, t)\psi_{\sigma}(\vec{r} + \frac{\vec{s}}{2}, t)$$

$$2 f_0(\vec{r}, \vec{p}, t) = f_{1,1}(\vec{r}, \vec{p}, t) + f_{-1,-1}(\vec{r}, \vec{p}, t),$$

$$2 g_x(\vec{r}, \vec{p}, t) = f_{-1,1}(\vec{r}\vec{p}, t) + f_{1,-1}(\vec{r}, \vec{p}, t),$$

$$2 g_y(\vec{r}, \vec{p}, t) = -i[f_{-1,1}(\vec{r}, \vec{p}, t) - f_{1,-1}(\vec{r}, \vec{p}, t)],$$

$$2 g_z(\vec{r}, \vec{p}, t) = f_{1,1}(\vec{r}, \vec{p}, t) - f_{-1,-1}(\vec{r}, \vec{p}, t).$$

R.F. O'Connell and E.P. Wigner, PRA (1984)

Spin-dependent equations of motion

Assuming $\vec{g}(\vec{r},\vec{p}) = \vec{n} f_1(\vec{r},\vec{p})$ **, define** $f^{\pm} = f_0 \pm f_1$ **,** $V_{hn} = \vec{h} \cdot \vec{n}$

spin-dependent Boltzmann-Vlasov Equation ⇒

$$\frac{\partial \vec{n}}{\partial t} \approx \frac{2\vec{h} \times \vec{n}}{\hbar}$$

procession of spin expectation direction

$$\frac{\partial f^{\pm}}{\partial t} + \left(\frac{\partial \varepsilon}{\partial \vec{p}} \pm \frac{\partial V_{hn}}{\partial \vec{p}}\right) \cdot \frac{\partial f^{\pm}}{\partial \vec{r}} - \left(\frac{\partial \varepsilon}{\partial \vec{r}} \pm \frac{\partial V_{hn}}{\partial \vec{r}}\right) \cdot \frac{\partial f^{\pm}}{\partial \vec{p}} = 0$$

Based on the test-particle method in C. Y. Wong, PRC (1982)

$$f^{+}(\vec{r},\vec{p},t) = \int \frac{d^3 r_0 d^3 p_0 d^3 s}{(2\pi\hbar)^3} \exp\{i\vec{s} \cdot [\vec{p} - \vec{P}(\vec{r}_0 \vec{p}_0 \vec{s},t)]/\hbar\}\, \delta[\vec{r} - \vec{R}(\vec{r}_0 \vec{p}_0 \vec{s},t)] f^{+}(\vec{r}_0,\vec{p}_0,t_0)$$

$$\left[-\frac{\partial \vec{R}(\vec{r}_0 \vec{p}_0 \vec{s},t)}{\partial t} + \frac{\partial \varepsilon}{\partial \vec{p}}\right] \cdot \frac{\partial f^{+}(\vec{r},\vec{p},t)}{\partial \vec{r}} + \frac{\partial V_{hn}}{\partial \vec{p}} \cdot \frac{\partial f^{+}(\vec{r},\vec{p},t)}{\partial \vec{r}} = 0$$

⇒

$$\frac{\partial \vec{R}(\vec{r}_0 \vec{p}_0 \vec{s},t)}{\partial t} = \frac{\partial \varepsilon}{\partial \vec{p}} + \frac{\partial V_{hn}}{\partial \vec{p}}$$

$$f^{+}(\vec{r}_0,\vec{p}_0,t_0)\left[\frac{-i\vec{s}}{\hbar} \cdot \frac{\partial \vec{P}(\vec{r}_0 \vec{p}_0 \vec{s},t)}{\partial t} - \frac{\varepsilon(\vec{r} - \frac{\vec{s}}{2},t) - \varepsilon(\vec{r} + \frac{\vec{s}}{2},t)}{i\hbar}\right] - f^{+}(\vec{r}_0,\vec{p}_0,t_0)\left[\frac{V_{hn}(\vec{r} - \frac{\vec{s}}{2},t) - V_{hn}(\vec{r} + \frac{\vec{s}}{2},t)}{i\hbar}\right] = 0$$

⇒

$$\frac{\partial \vec{P}(\vec{r}_0 \vec{p}_0 \vec{s},t)}{\partial t} = -\frac{\partial \varepsilon}{\partial \vec{r}} - \frac{\partial V_{hn}}{\partial \vec{r}}$$

Skyrme-type spin-orbit interaction

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

single-particle energy

spin-independent $\varepsilon = \frac{p^2}{2m} + U_{MID} + \varepsilon_{so}$

$$\varepsilon_{so} = -\frac{W_0}{2}\nabla \cdot (\vec{J} + \vec{J}_\tau) - \frac{W_0}{2}[\vec{p} \cdot (\nabla \times (\vec{s} + \vec{s}_\tau))]$$

spin-dependent

$$\vec{h} = -\frac{W_0}{2}\nabla \times (\vec{j} + \vec{j}_\tau) + \frac{W_0}{2}[\nabla(\rho + \rho_\tau) \times \vec{p}]$$

equations of motion

$$\frac{d\vec{r}_i}{dt} = \frac{\partial}{\partial \vec{p}_i}(\varepsilon + \vec{h} \cdot \vec{\sigma}_i),$$

$$\frac{d\vec{p}_i}{dt} = -\frac{\partial}{\partial \vec{r}_i}(\varepsilon + \vec{h} \cdot \vec{\sigma}_i),$$

$$\frac{d\vec{\sigma}_i}{dt} = 2\frac{\vec{h} \times \vec{\sigma}_i}{\hbar}.$$

number density **(time-even)**

$$\rho(\vec{r}) = 2\int d^3p f_0(\vec{r}, \vec{p}),$$

spin density **(time-odd)**

$$\vec{s}(\vec{r}) = 2\int d^3p \vec{g}(\vec{r}, \vec{p}),$$

current density **(time-odd)**

$$\vec{j}(\vec{r}) = 2\int d^3p \frac{\vec{p}}{\hbar} f_0(\vec{r}, \vec{p}),$$

spin-current density **(time-even)**

$$\vec{J}(\vec{r}) = 2\int d^3p \frac{\vec{p}}{\hbar} \times \vec{g}(\vec{r}, \vec{p}).$$

Lattice Hamiltonian method

$$\rho_L(\vec{r}_\alpha) = \sum_i S(\vec{r}_\alpha - \vec{r}_i),$$

$$\vec{s}_L(\vec{r}_\alpha) = \sum_i \vec{\sigma}_i S(\vec{r}_\alpha - \vec{r}_i),$$

$$\vec{j}_L(\vec{r}_\alpha) = \sum_i \frac{\vec{p}_i}{\hbar} S(\vec{r}_\alpha - \vec{r}_i),$$

$$\vec{J}_L(\vec{r}_\alpha) = \sum_i \left(\frac{\vec{p}_i}{\hbar} \times \vec{\sigma}_i\right) S(\vec{r}_\alpha - \vec{r}_i).$$

Spin singlet and spin triplet

spin expectation direction $\vec{\sigma} = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$ **spin state in z direction** $\chi = \begin{pmatrix} e^{\frac{-i\phi}{2}}\cos\frac{\theta}{2} \\ e^{\frac{i\phi}{2}}\sin\frac{\theta}{2} \end{pmatrix}$

spin state of two particles

$$\Psi = \chi_1 \otimes \chi_2 = \begin{pmatrix} e^{\frac{-i(\phi_1+\phi_2)}{2}}\cos\frac{\theta_1}{2}\cos\frac{\theta_2}{2} \\ e^{\frac{-i(\phi_1-\phi_2)}{2}}\cos\frac{\theta_1}{2}\sin\frac{\theta_2}{2} \\ e^{\frac{i(\phi_1-\phi_2)}{2}}\sin\frac{\theta_1}{2}\cos\frac{\theta_2}{2} \\ e^{\frac{i(\phi_1+\phi_2)}{2}}\sin\frac{\theta_1}{2}\sin\frac{\theta_2}{2} \end{pmatrix}$$

define $|\uparrow\uparrow\rangle = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}, \quad |\uparrow\downarrow\rangle = \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix}, \quad |\downarrow\uparrow\rangle = \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix}, \quad |\downarrow\downarrow\rangle = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}$

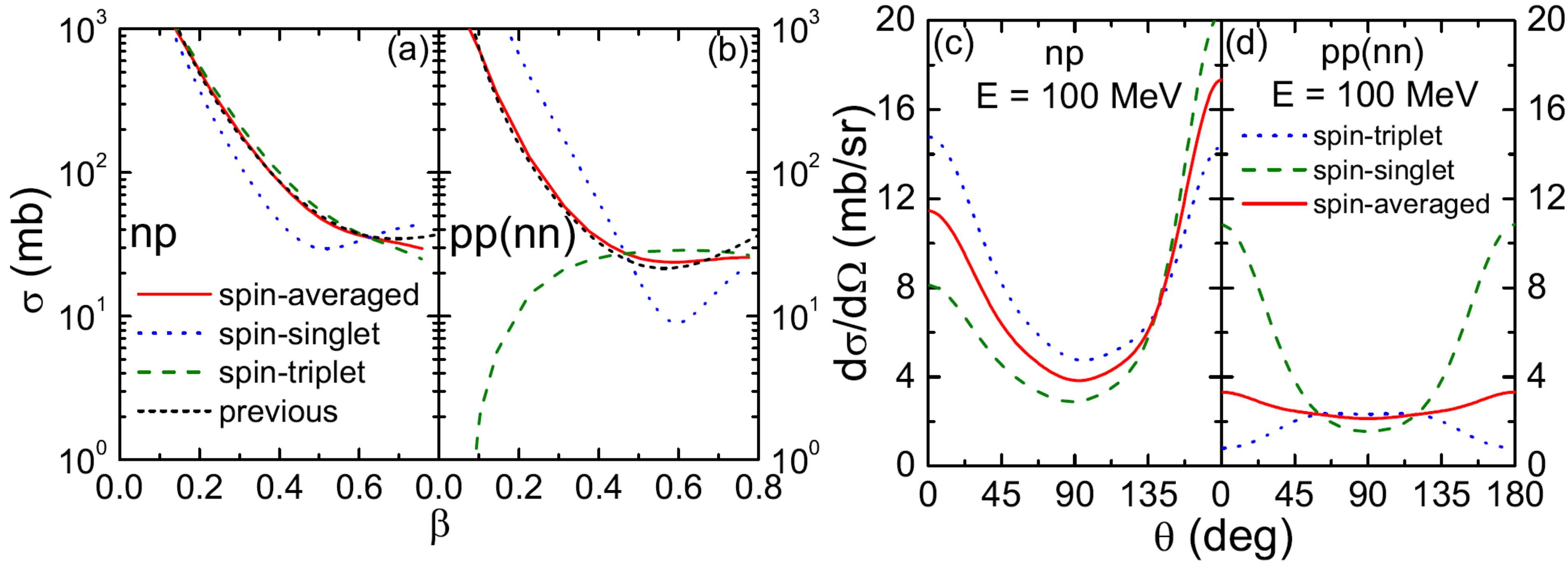
spin singlet $\chi_{0,0} = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} \\ 0 \end{pmatrix}$ **spin triplet** $\chi_{1,1} = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}, \ \chi_{1,0} = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \\ 0 \end{pmatrix}, \ \chi_{1,-1} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}$

normalization condition

$$|\langle\chi_{0,0}|\Psi\rangle|^2 + |\langle\chi_{1,1}|\Psi\rangle|^2 + |\langle\chi_{1,0}|\Psi\rangle|^2 + |\langle\chi_{1,-1}|\Psi\rangle|^2 = 1$$

Spin-dependent NN scatterings

np and pp phase shift data R. A. Arndt *et al.*, PRC (1977)



"previous":

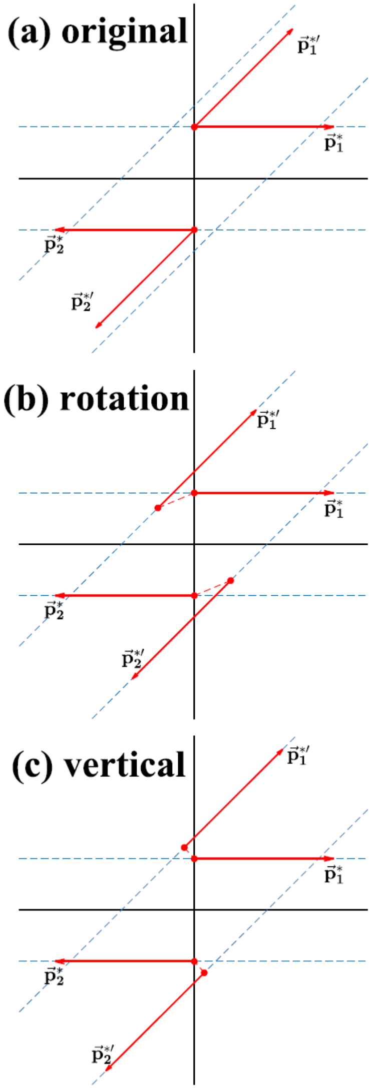
$$\sigma_{pp(nn)} = 8.76/\beta^2 - 15.04/\beta + 13.73 + 68.76\beta^4,$$

$$\sigma_{np} = 25.26/\beta^2 - 18.18/\beta - 70.67 + 113.85\beta,$$

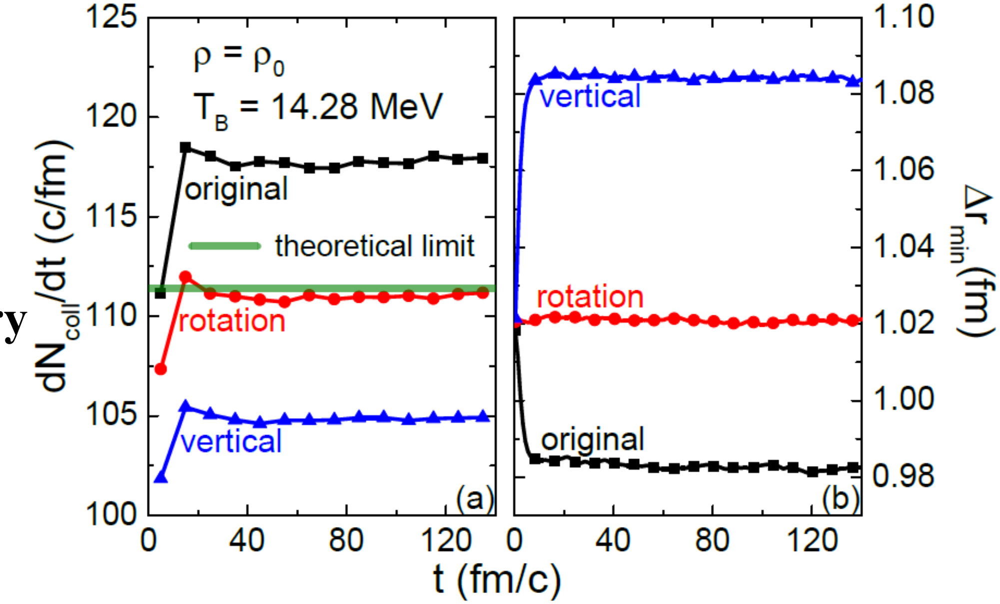
- **spin-dependent Pauli blocking**
- ***rigorous angular momentum conservation***

Constraint of angular momentum conservation

in-plane scatterings
(modified after incorporating spin)

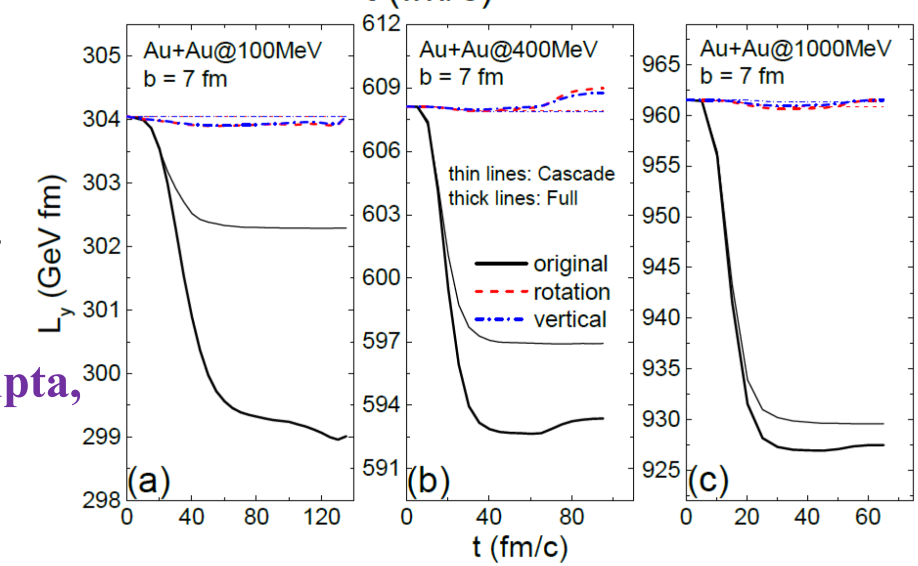


collision rate in box with periodic boundary condition



evolution of angular momentum in HIC

C. Gale and S. Das Gupta, PRC (1990)



Spin-dependent coalescence

traditional coalescence

$$f_d = 8g_d \exp\left(-\frac{\rho^2}{\sigma_d^2} - p_\rho^2\sigma_d^2\right),$$

$$f_{t/^3He} = 8^2 g_{t/^3He} \exp\left(-\frac{\rho^2+\lambda^2}{\sigma_{t/^3He}^2} - \left(p_\rho^2 + p_\lambda^2\right)\sigma_{t/^3He}^2\right).$$

statistical factor $g_d = 3/4 \quad g_{t/^3He} = 1/4$

spin expectation direction $\vec{\sigma} = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$

deuteron： **spin 1, np spin triplet**

$$\begin{aligned} g_d &= |\langle\chi_{1,1}\mid\Psi\rangle|^2 + |\langle\chi_{1,0}\mid\Psi\rangle|^2 + |\langle\chi_{1,-1}\mid\Psi\rangle|^2 \\ &= 1 - |\langle\chi_{0,0}\mid\Psi\rangle|^2 \\ &= \frac{1}{4}\left[3 + \cos\theta_1\cos\theta_2 + \sin\theta_1\sin\theta_2\cos(\phi_1-\phi_2)\right] \end{aligned}$$

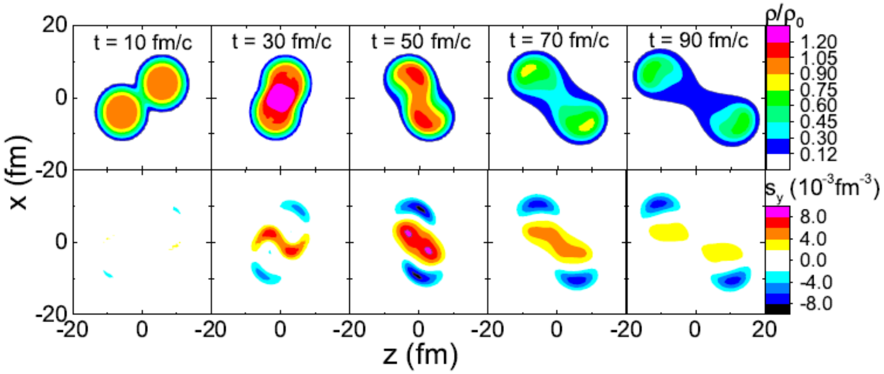
$$\begin{aligned} \rho_{0,0} &= \frac{|\langle\chi_{1,0}\mid\Psi\rangle|^2}{1 - |\langle\chi_{0,0}\mid\Psi\rangle|^2} \\ &= \frac{1 - \cos\theta_1\cos\theta_2 + \sin\theta_1\sin\theta_2\cos(\phi_1-\phi_2)}{3 + \cos\theta_1\cos\theta_2 + \sin\theta_1\sin\theta_2\cos(\phi_1-\phi_2)} \end{aligned}$$

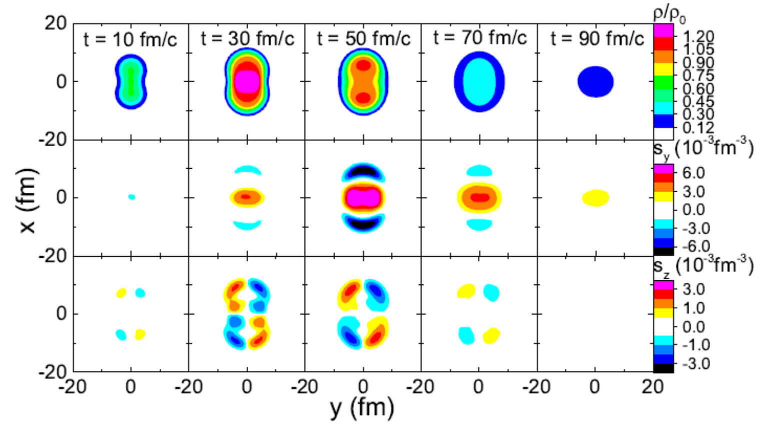
triton (^{3}He)： **spin 1/2 determined by residue n(p), np spin singlet**

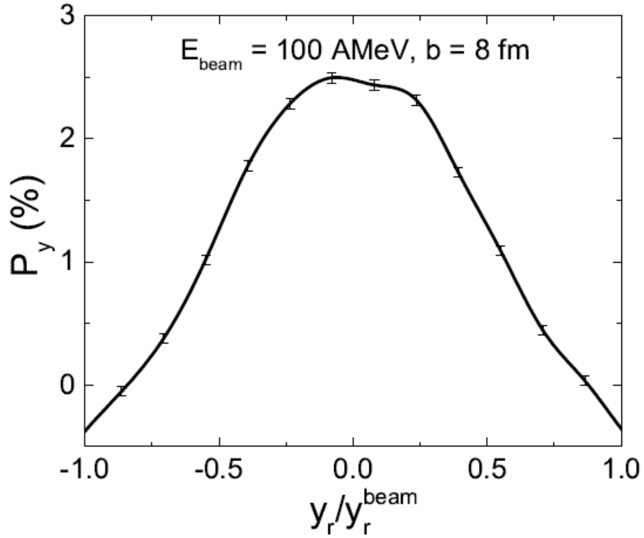
$$g_{t/^3He} = |\langle\chi_{0,0}\mid\Psi\rangle|^2 = \frac{1}{4}\left[1 - \cos\theta_1\cos\theta_2 - \sin\theta_1\sin\theta_2\cos(\phi_1-\phi_2)\right]$$

Nucleon spin polarization in HIC

Au+Au@100MeV

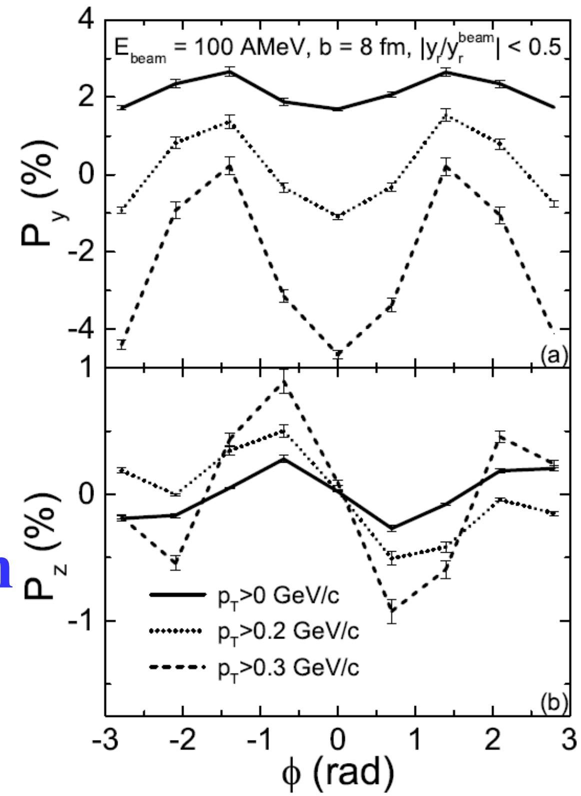




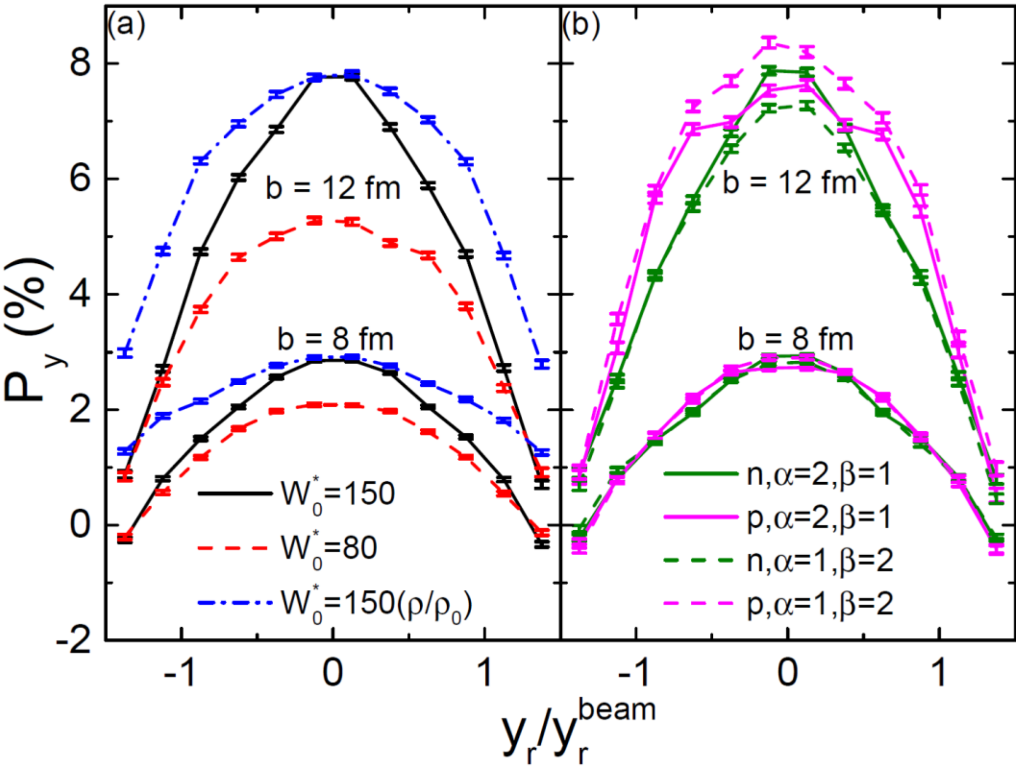


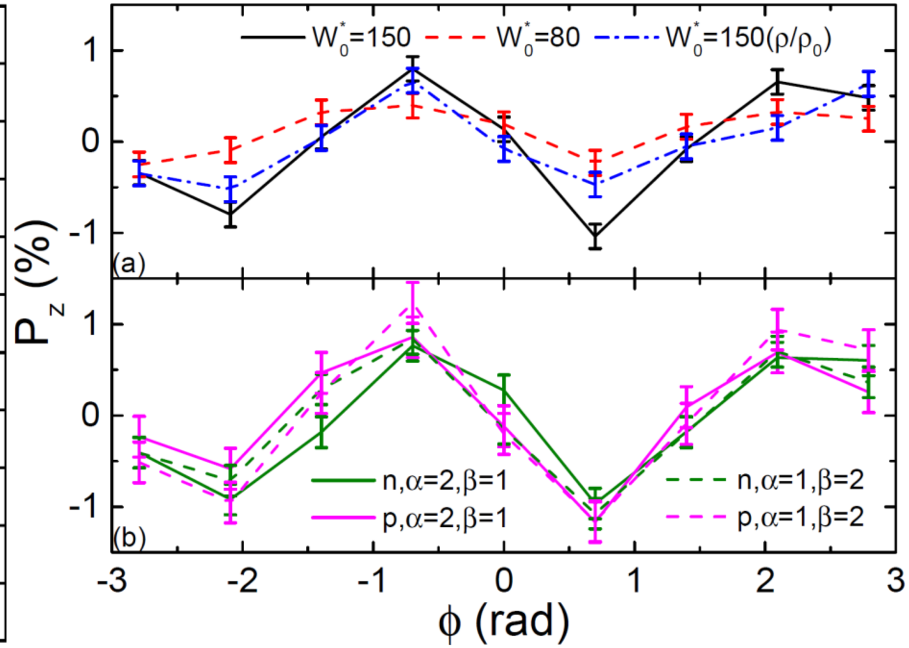
$$P_y = \frac{N_{\mathfrak{s}_y=+\frac{1}{2}} - N_{\mathfrak{s}_y=-\frac{1}{2}}}{N_{\mathfrak{s}_y=+\frac{1}{2}} + N_{\mathfrak{s}_y=-\frac{1}{2}}}$$

sign problem



Nucleon spin polarization from different SO potentials



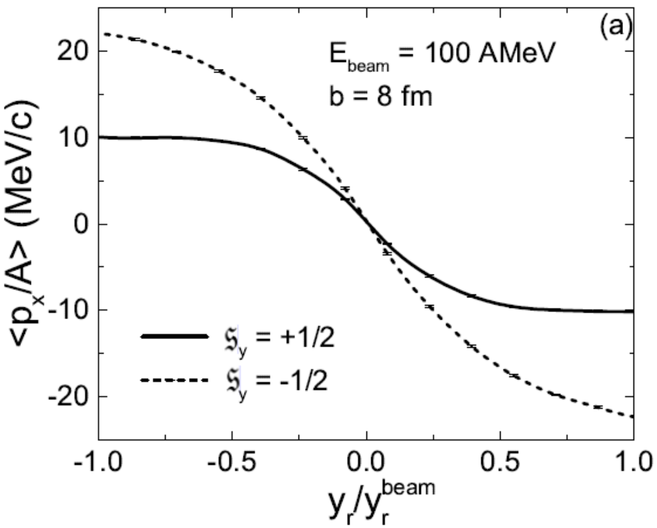


$$\overrightarrow{W_q} = W_0 \left(\frac{\rho}{\rho_0}\right)^{\gamma} (\alpha \nabla \rho_q + \beta \nabla \rho_{q'}) \quad (q \neq q')$$

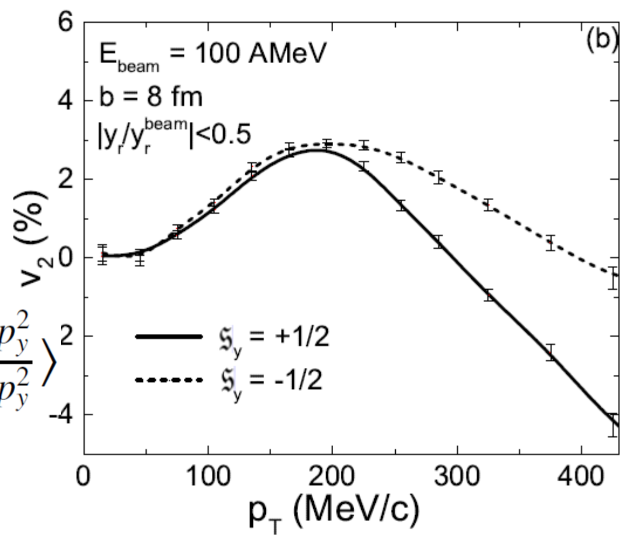
Spin dynamics and nucleon collective flow

spin splitting of collective flow

transverse flow

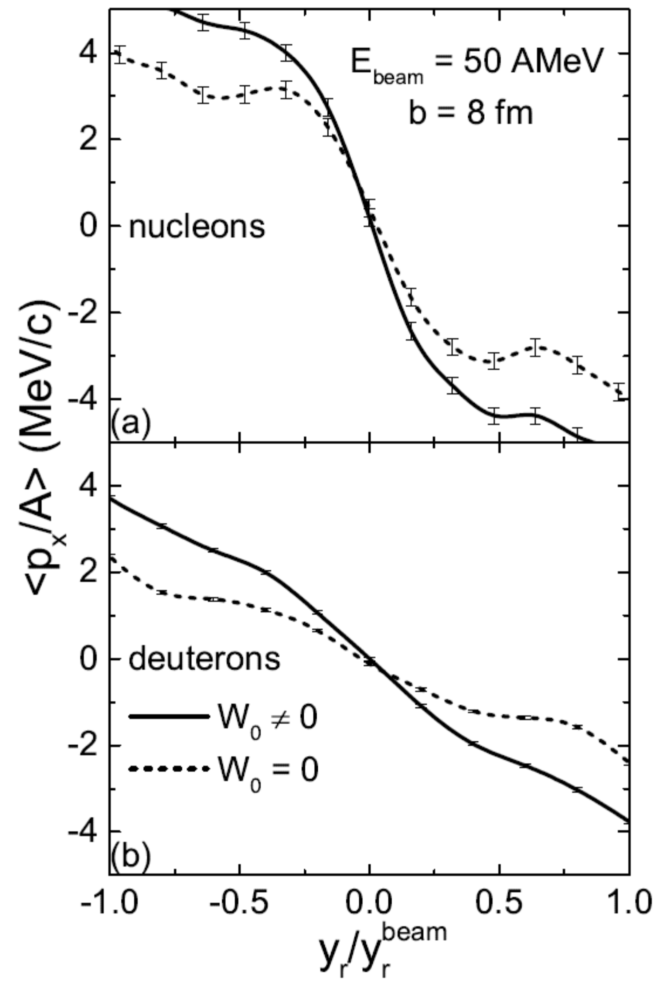


elliptic flow



$$v_2 = \langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \rangle$$

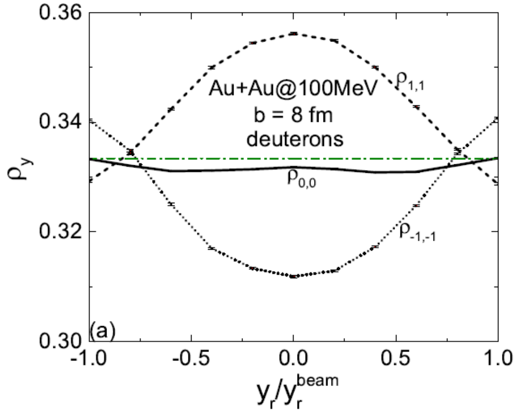
spin-averaged collective flow



Spin dynamics of light nuclei

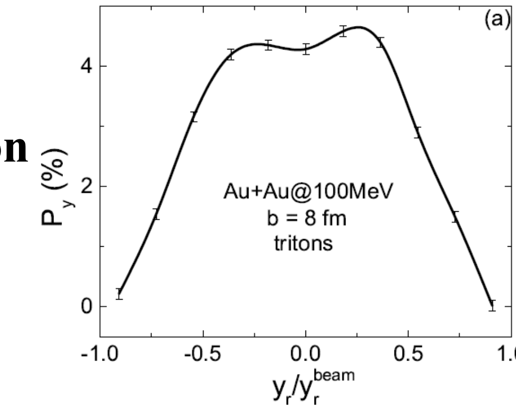
deuterons

spin alignment in y direction

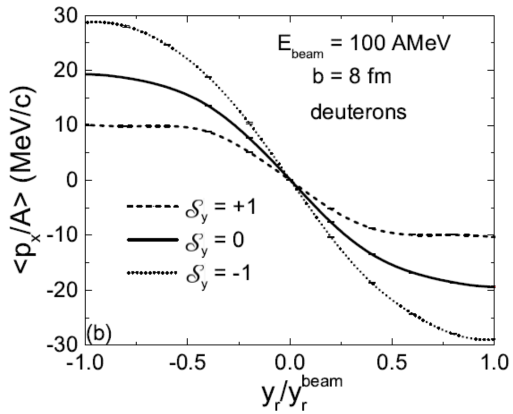


tritons

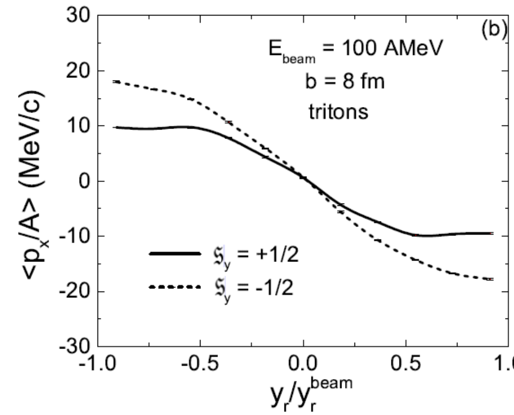
spin polarization in y direction



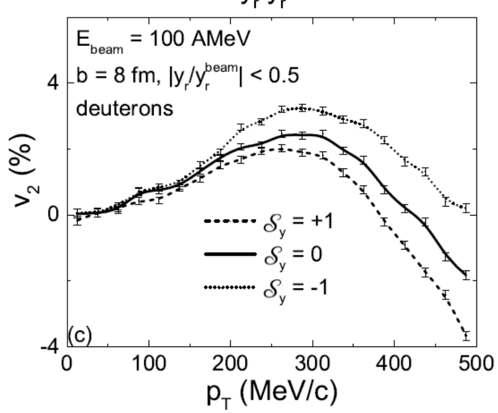
transverse flow



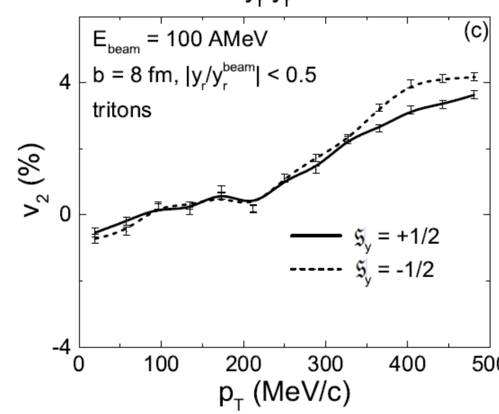
transverse flow



elliptic flow

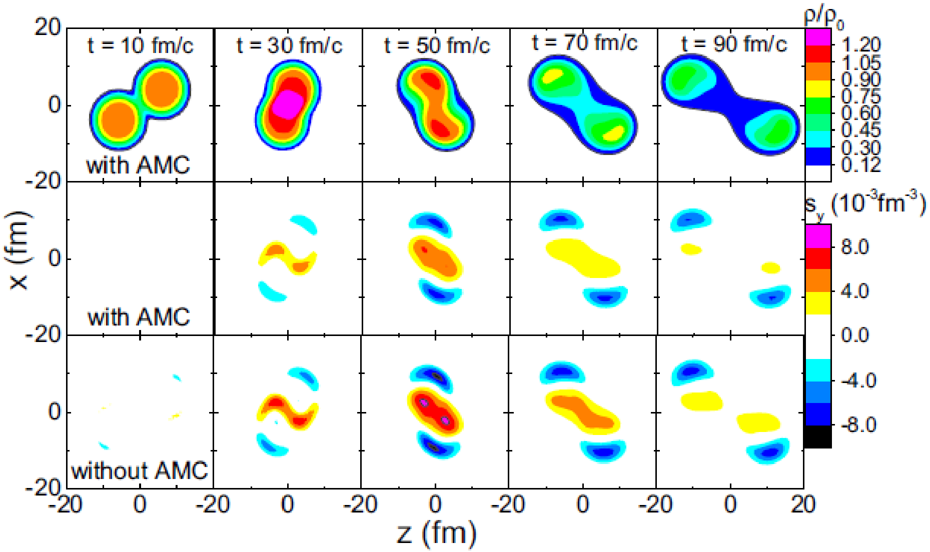


elliptic flow

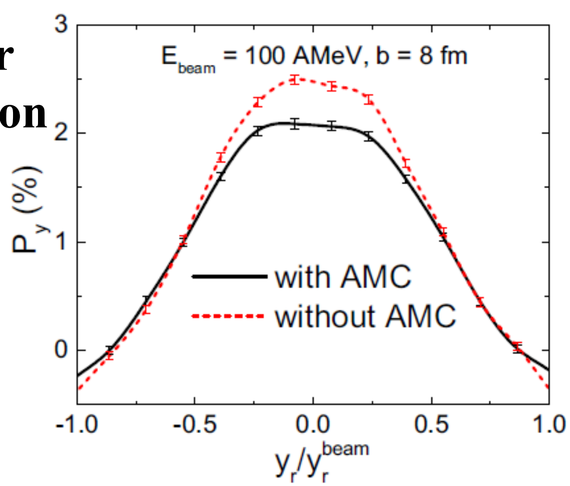


Constraint of
Angular Momentum Conservation (AMC) - vertical

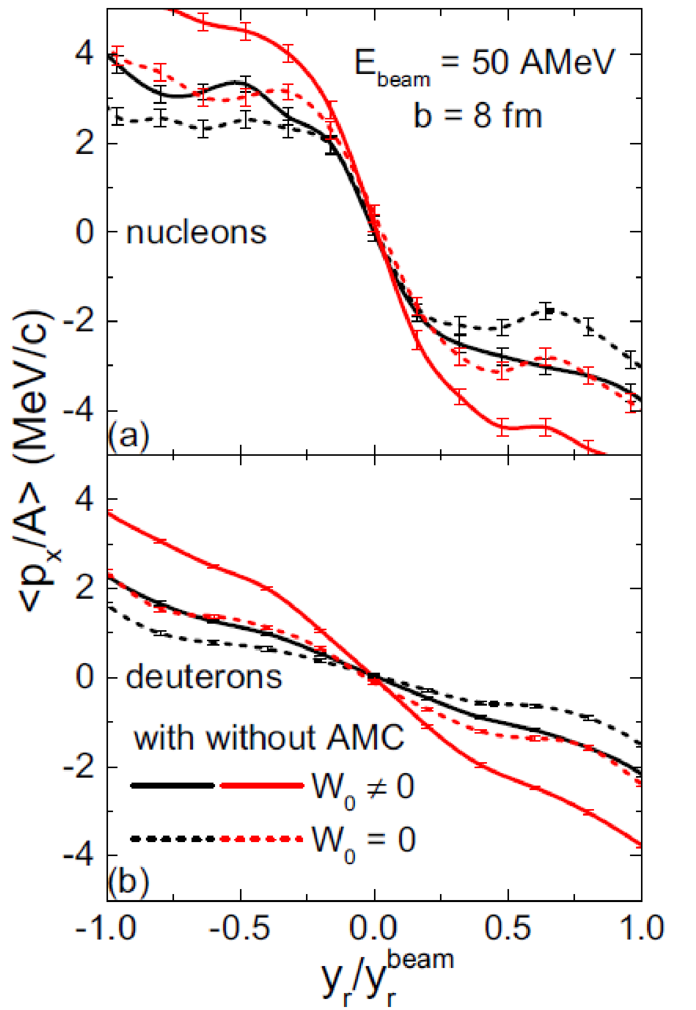
lower number and spin densities



slightly weaker spin polarization

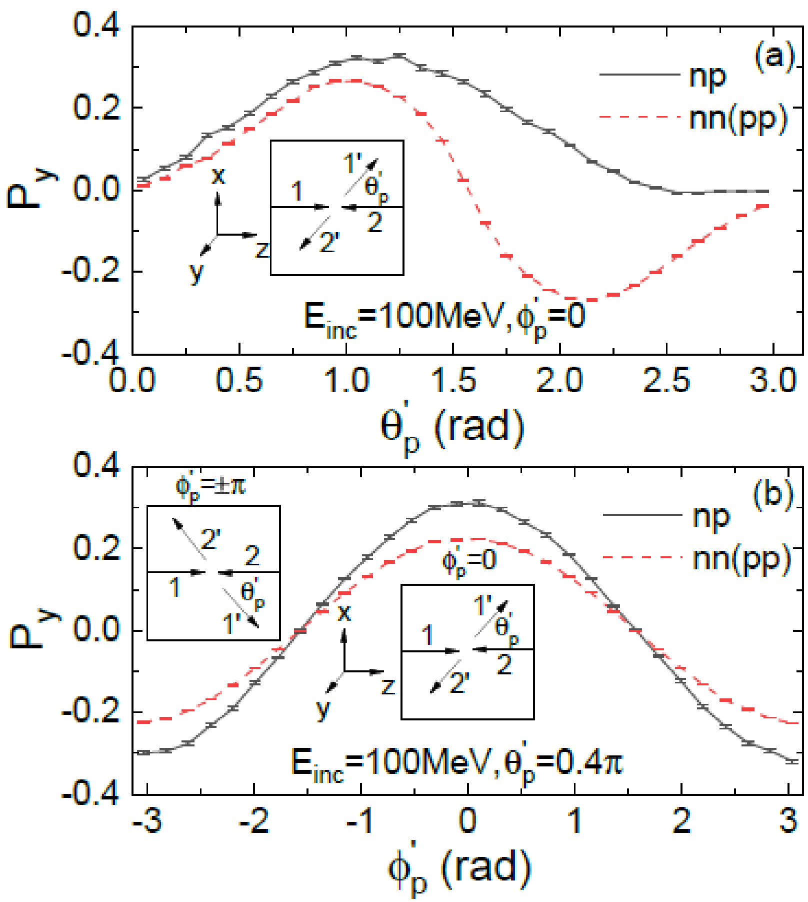


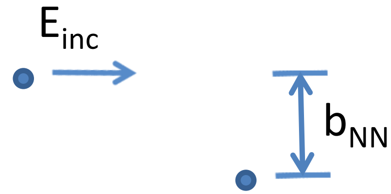
Affect spin-averaged collective flow



Nucleon spin change after NN scatterings

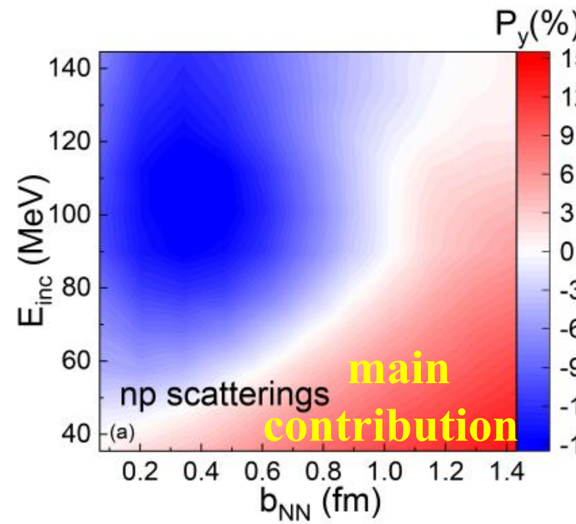
$$\frac{\partial \hat{f}}{\partial t} + \frac{i}{\hbar}\left[\hat{\varepsilon}, \hat{f}\right] + \frac{1}{2}\left(\frac{\partial \hat{\varepsilon}}{\partial \vec{p}} \cdot \frac{\partial \hat{f}}{\partial \vec{r}} + \frac{\partial \hat{f}}{\partial \vec{r}} \cdot \frac{\partial \hat{\varepsilon}}{\partial \vec{p}}\right) - \frac{1}{2}\left(\frac{\partial \hat{\varepsilon}}{\partial \vec{r}} \cdot \frac{\partial \hat{f}}{\partial \vec{p}} + \frac{\partial \hat{f}}{\partial \vec{p}} \cdot \frac{\partial \hat{\varepsilon}}{\partial \vec{r}}\right) = I_c$$

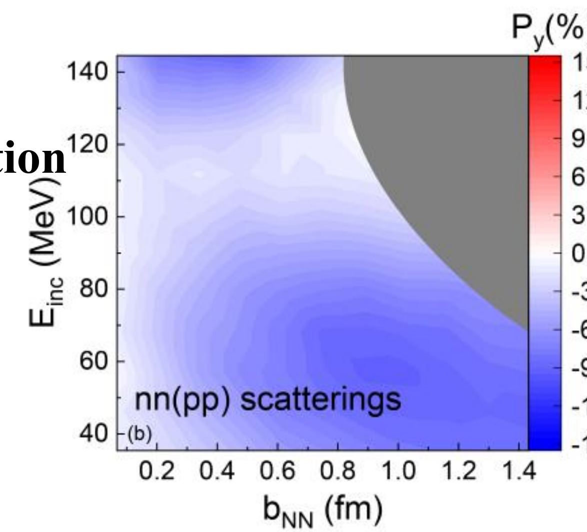




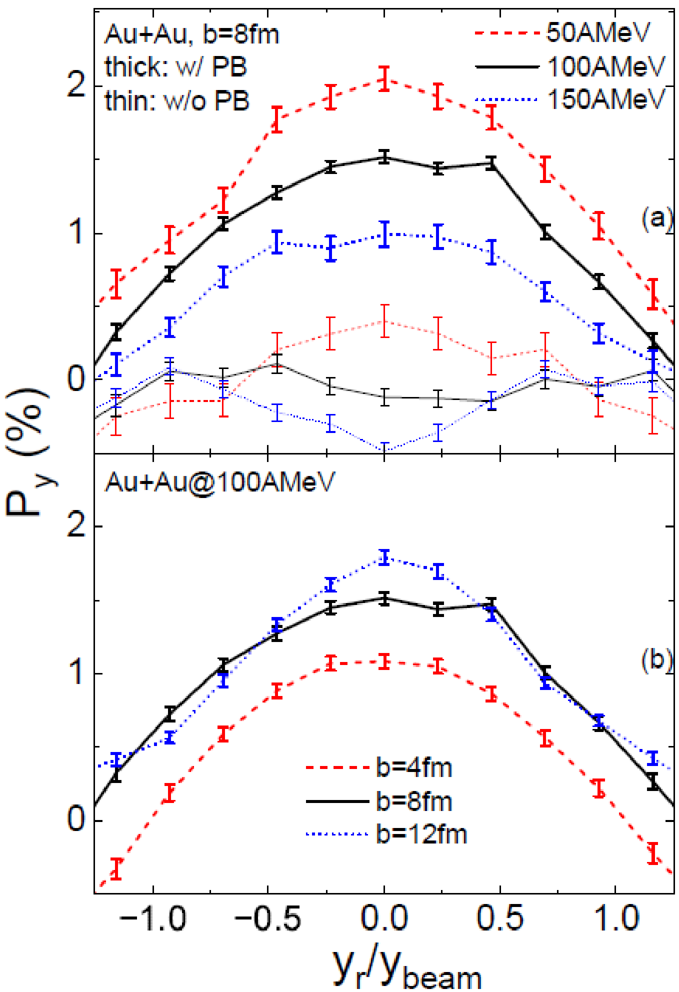
nucleon spin change from phase-shift data

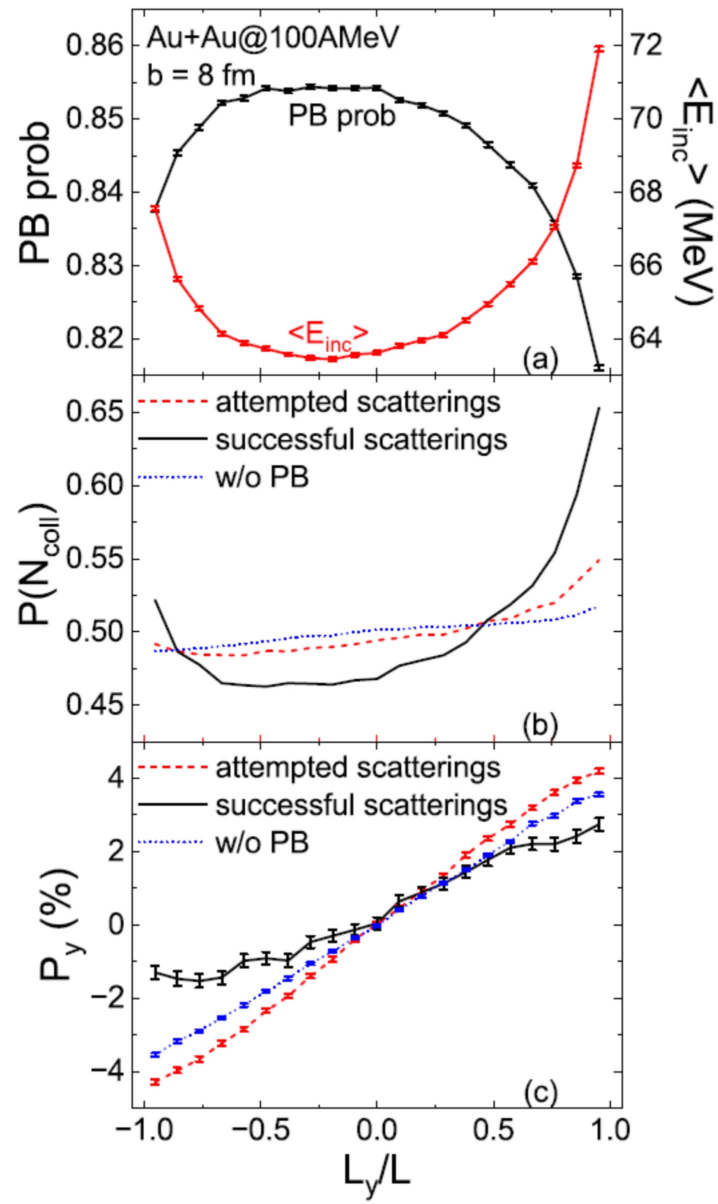
rigorous angular momentum conservation





Spin polarization from only NN scatterings





Outlook

- **In-medium phase-shift data**
- **Experimental observables**
  - **excited states of light nuclei**
  - **dynamics of Δ and π**
  - **hyperons and vector mesons**

Thank you!

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