Effective mass of nucleons in the nucleus in multistep direct (p,p'x) and (p,nx) to continuum

RCNP 研究会
「中間エネルギーイオンビームによる物理」

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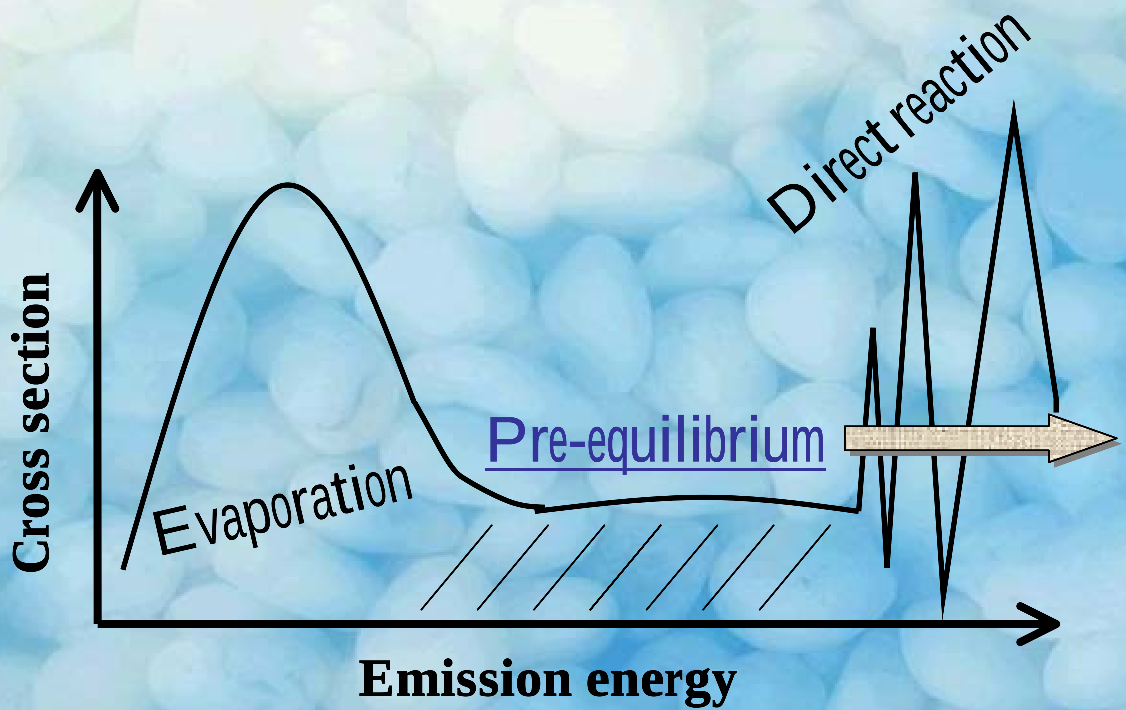
□ References

- K. Ogata *et al*., to be published in NPA.; to be submitted to PRL.
- Y. Watanabe *et al*., PRC**59**, 2136 (1999).
- K. Ogata *et al*., PRC**60**, 054605 (1999).
- Sun Weili *et al*., PRC**60**, 064605 (1999).
- T. Wakasa *et al*., PRC**65**, 034615 (2002).

Pre-equilibrium MSD process

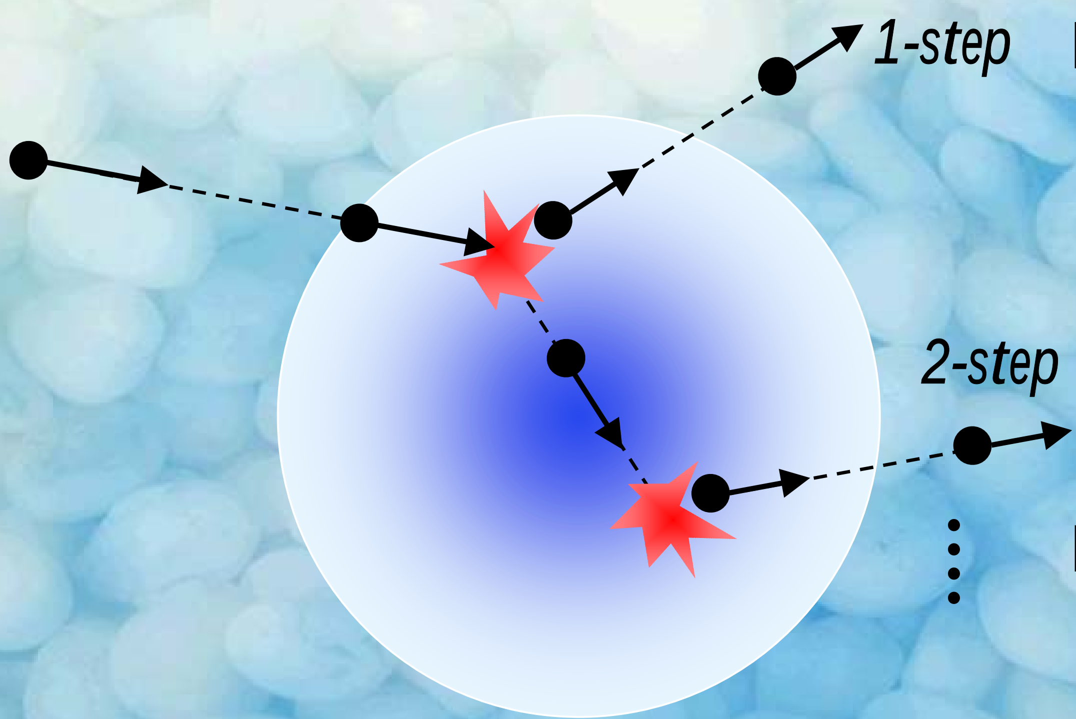


- **Excitation to continuum**
- **Multiple scattering**
- **No compound nucleus**

Various models have been proposed:

- Phenomenological methods of simulation: **INC** and **Exciton model**
- Quantum mechanical models: **FKK**, **NWY** and **TUL**
- Microscopic methods of simulation: **QMD** and **AMD**

Picture of MSD



- MSD is described by:
  - Series of excitation of the target nucleus
  - Successive collisions between leading particle and nucleons in the target
- Cross Section is obtained by taking summation over all ‘paths’:
  - Number of excitation (= Step)
  - Position of individual collision points
  - Energy transfer for each process
  - Nuclear (single particle) states in the initial and the final channels

➢ **Key for this simple picture**

Incoherent Sum

⇩

No Interference

The SCDW model

- **Starting from the DWBA series expansion for the *T* matrix**
  - The never come back assumption separates individual steps.
- **Calculation for the one-step DDX**
  - Local semiclassical approximation (LSCA) to the distorted waves

$$\chi_c(\mathbf{R} \pm \mathbf{s}) \cong \chi_c(\mathbf{R}) \exp\{\pm i\, \mathbf{k}_c(\mathbf{R}) \cdot \mathbf{s}\}, \quad c = i, f$$

  - Incorporation of the Wigner transform of a one-body density matrix

$$\frac{\partial^2 \sigma^{\text{1step}}}{\partial E_f \partial \Omega_f} = \frac{C}{(2\pi)^3} \frac{k_f}{k_i} \int d\mathbf{R} \left|\chi_f(\mathbf{R})\right|^2 \times \left|\chi_i(\mathbf{R})\right|^2$$

$$\times \int d\mathbf{k}_\alpha d\mathbf{k}_\beta \;\; f_h(\mathbf{k}_\alpha, \mathbf{R})\, f_p(\mathbf{k}_\beta, \mathbf{R}) \;\; \frac{1}{2} \sum_{m_1 m_2 m_1' m_2' \nu_2} \left| \;M\; \right|^2$$

$$\times\, \delta\left(\mathbf{k}_\beta + \mathbf{k}_f(\mathbf{R}) - \mathbf{k}_\alpha - \mathbf{k}_i(\mathbf{R})\right) \delta\left(E_\beta - E_\alpha - \omega\right).$$

Extension to multistep processes

- **Eikonal approximation to the Green function**

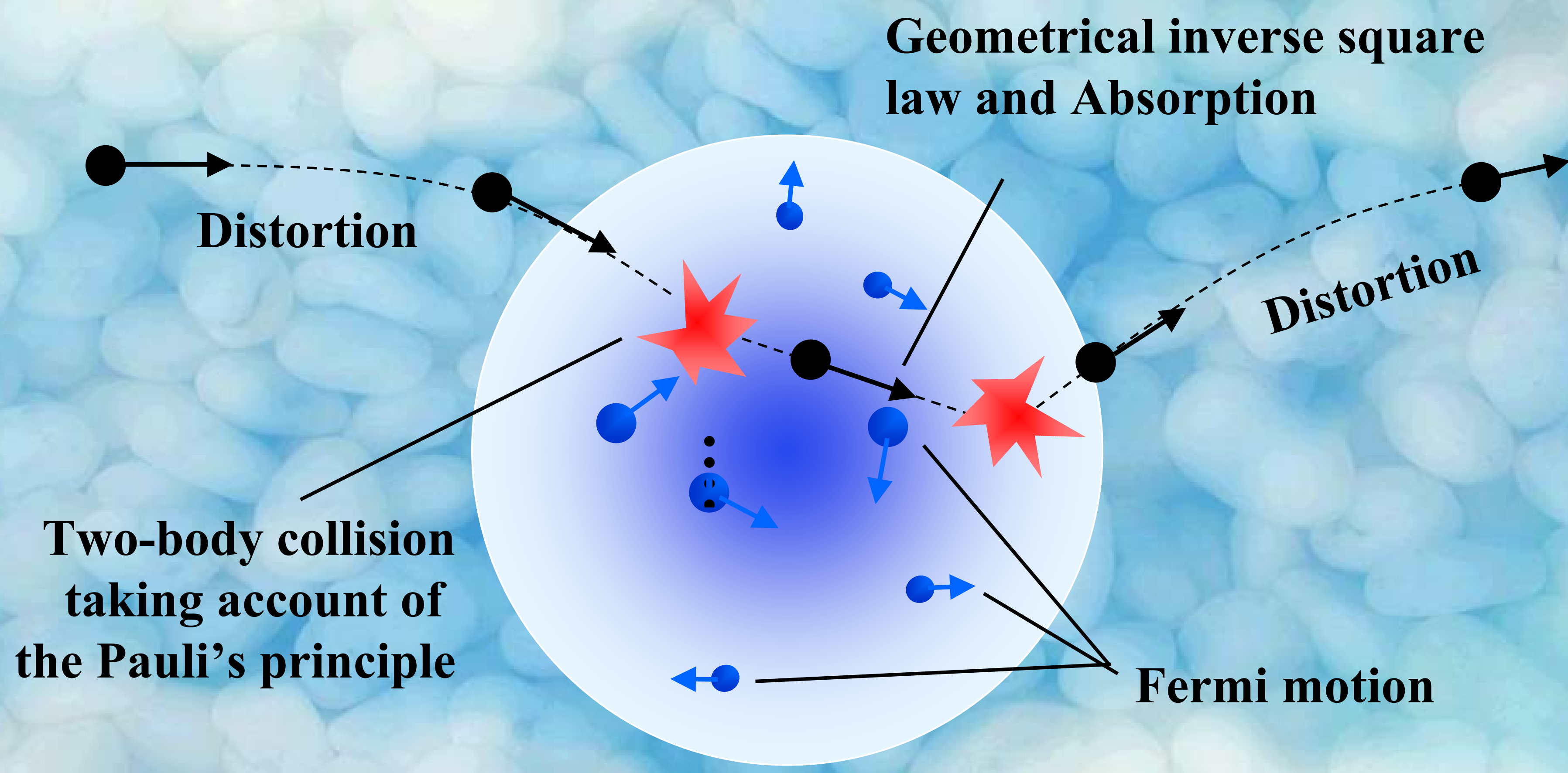
$$\langle \mathbf{R}_2 | (E_m - K - U_m + i\eta)^{-1} | \mathbf{R}_1 \rangle \cong -\frac{2\mu}{\hbar} \frac{\exp(i\, k_m |\mathbf{R}_2 - \mathbf{R}_1|)}{|\mathbf{R}_2 - \mathbf{R}_1|}$$

$$\mathbf{k}_m = \boldsymbol{\kappa}_m + i\, \boldsymbol{\gamma}_m$$

  - Valid for fast particle under slowly-varying potential
  - Geometrical inverse square law and absorption by the potential in the intermediate state are taken into account.

- **DDX formulae for multistep processes have simple closed form as for the one-step process.**

Schematic Illustration of SCDW



- No interference between processes through different collision points!

Effective mass approximation

- **In previous calculation we used 'bare mass' for a nucleon in the target nucleus.**
  - Agreement with data was rather good but unsatisfactory.
  - Analyses of electron scattering showed that inclusion of an effective mass is essential.

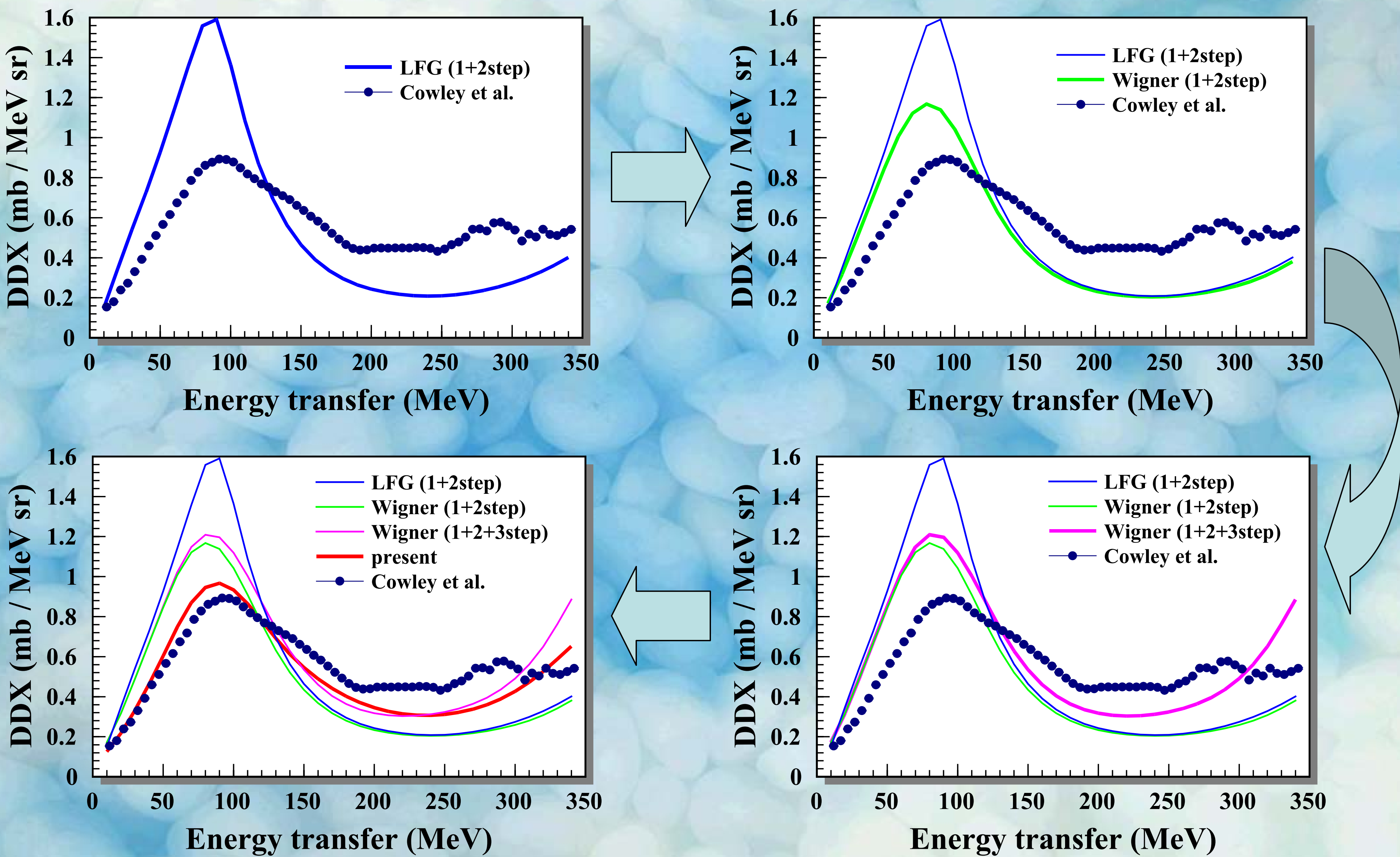
- **Origin of effective mass:**
  - Nonlocality of the single particle potential U for the target nucleus $\Longrightarrow$ 'k-mass'
  - Energy dependence of U $\Longrightarrow$ 'E-mass'

  ➢ **We include here m^* of Woods-Saxon form; m^* at the center of the nucleus is chosen to be $0.7m$ for proton and $0.8m$ for neutron**

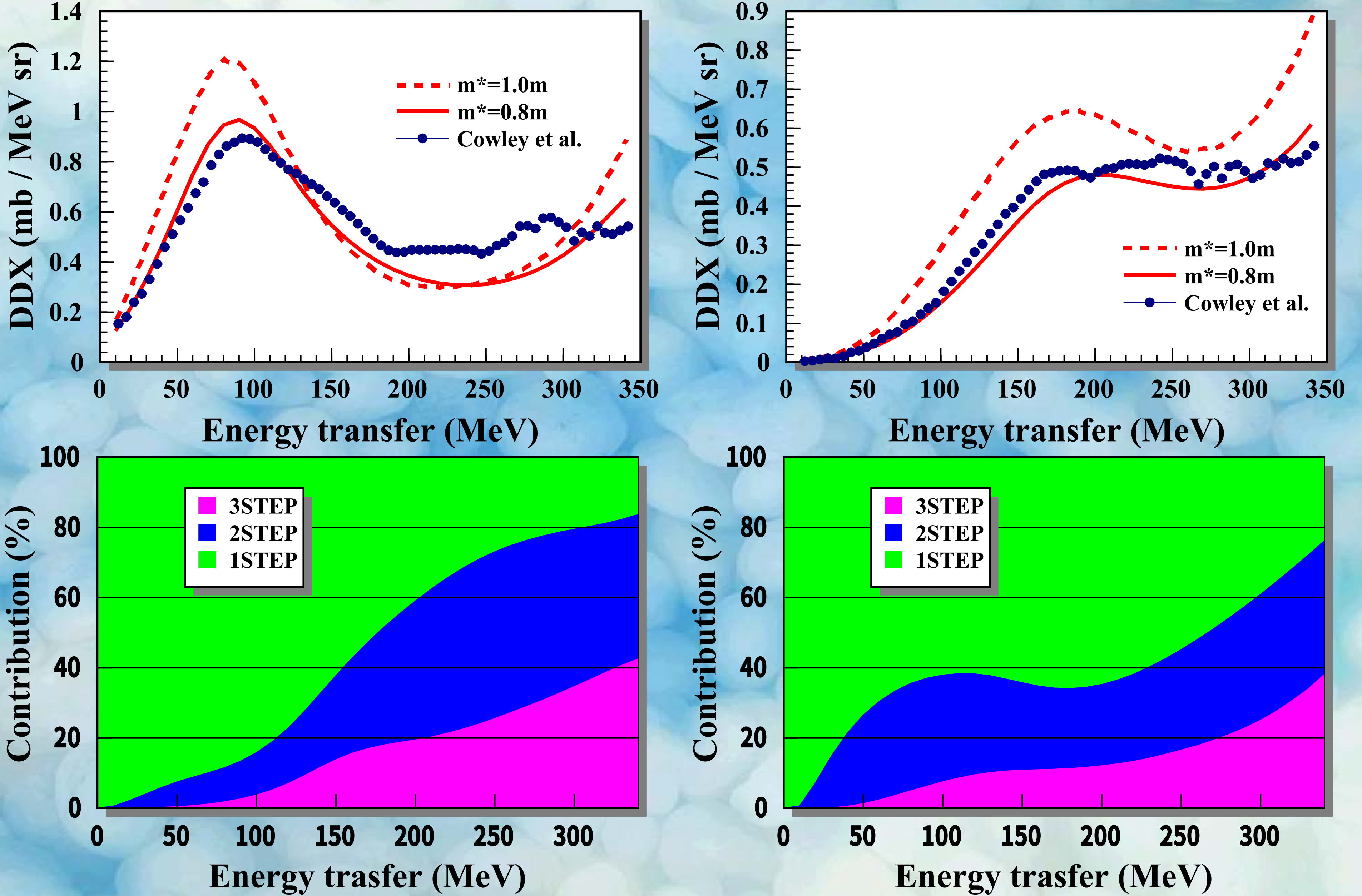
Input data

- **Distorting potentials**
  - Hama *et al.* (*p*) and Ishibashi *et al.* (*n*) based on Dirac phenomenology
- **Single particle potential for the nucleon in the target nucleus**
  - Global parameter set by Bohr and Motterson
- **Effective NN interaction in nuclear medium**
  - Half-off-shell *G* matrix in coordinate space based on Bonn-B N-N potential (by Melbourne group)
- **Nuclear density**
  - Negele's parameter set of Woods-Saxon forms
- **Nonlocality of distorting potentials**
  - Perey factor with range $\beta = 0.85$ fm
- **Multifold integral**
  - Monte Carlo integration method with Quasi Random Number

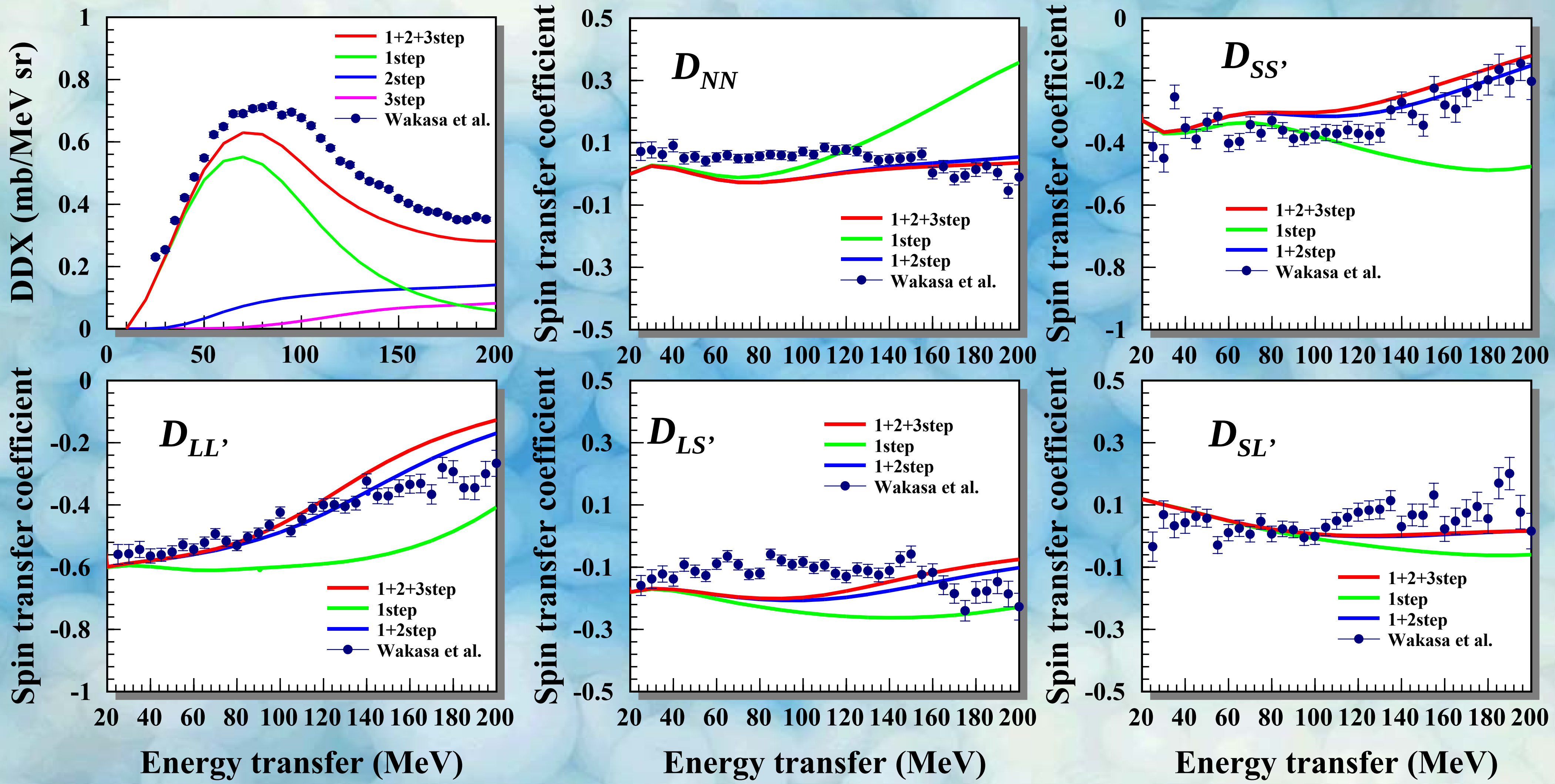
DDX for ^{40}Ca($p,p'x$) at 392 MeV and 25.5 deg.



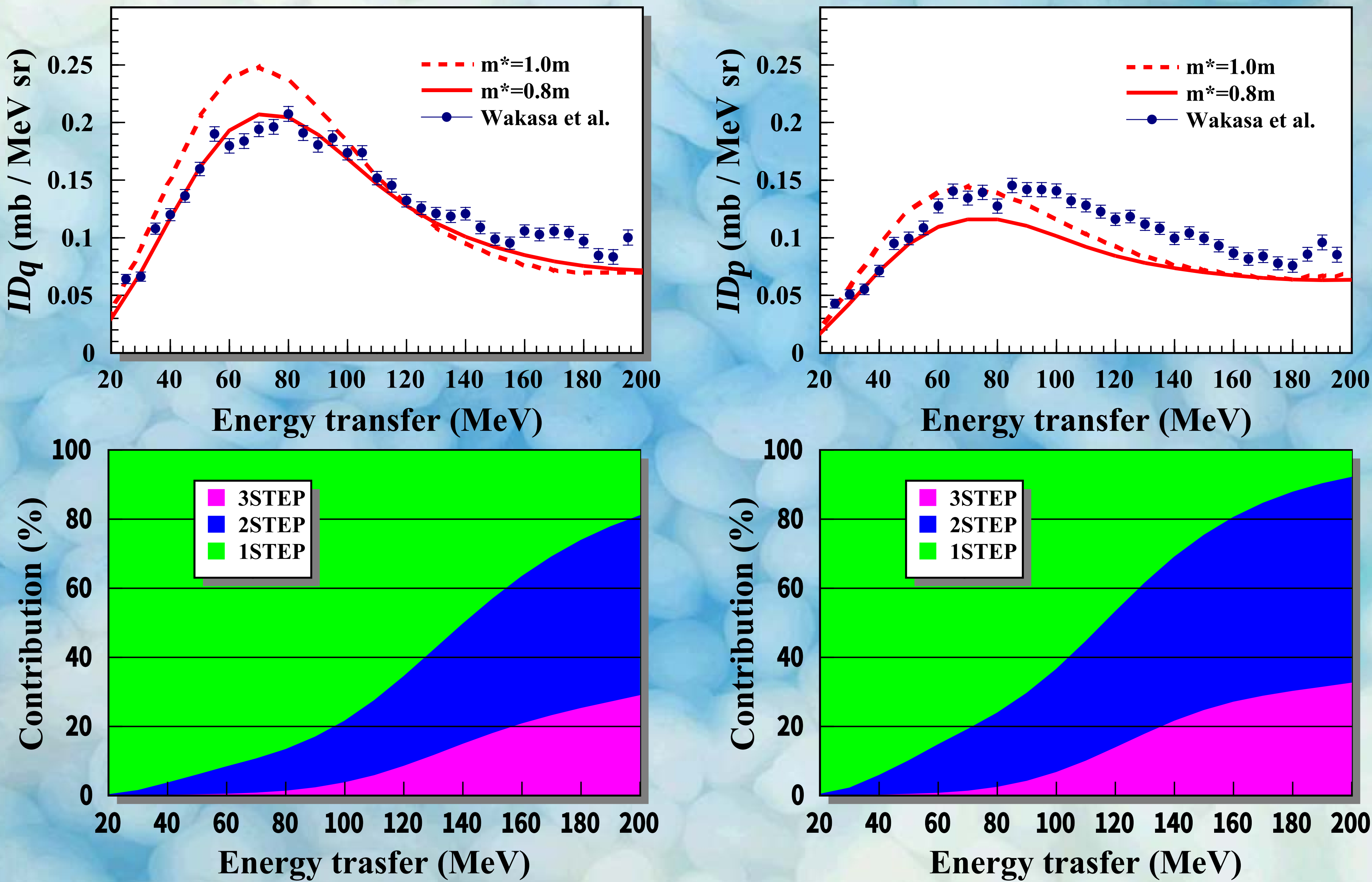
Analysis of the DDX for ^{40}Ca(*p,p'x*)@392 MeV



DDX and D_{ij} for ^{40}Ca(*p,nx*) at 346 MeV and 22 deg.



ID_i for $^{40}Ca(p,nx)$ at 346 MeV and 22 deg.



Summary and future work

☐ Summary

- The Semi-Classical Distorted Wave (SCDW) model for multistep direct (MSD) reactions was improved by using effective mass approximation.
- The calculated cross sections for ^{40}Ca(p,p'x) at 392 MeV and ^{40}Ca(p,nx) at 346 MeV well agree with experimental data.
- Effective mass plays important roles in the description of MSD (shape of energy spectra and quasi-free peak positions).
- Experimental data for the spin-longitudinal (ID_q) and transverse (ID_p) cross sections for ^{40}Ca(p,nx) at 346 MeV and 22 deg. are both well re-produced, except for the slight underestimation for the ID_p.

☐ Future work

- More realistic treatment of the effective mass
- Calculation of Analyzing power
- Angular dependence of D_{ij} comparing with the exp. data of IUCF.