Kinematics of (p, pX) knocout reactions in normal and inverse kinematics†

T. Uesaka*1

Proton-induced knockout reactions are major experimental tools at several hundred MeV and has been adapted in many experiments at RIBF, RCNP, and GSI. Recently an experimental program using (p, pX) knockout reactions, ONOKORO project has started to explore cluster structure in unstable nuclei.

One of the advantages of the (p, pX) knockout reactions is flexibility in their kinematics. Since the final state consists of three particles, a scattered proton, a knocked-out particle, and a residual nucleus, the kinematical conditions of the elementary process and the orbital motion of the knocked-out particle can be separated with considerable freedom even for a fixed incident energy.

The price for the flexibility is slightly more complexity in kinematics. In addition to the number of particles (=3) in the final state, several points prevent quick understanding of the kinematics: 1) the binding energy and the Fermi motion of the particle X in a target nucleus make a sub-system of the reaction off the energy shell. 2) in-nucleus momentum of the particle X, which is a quantity of interest, is not a direct observable and not explicitly used often in literature. 3) The relationship between observed quantities and key physical quantities of the reaction differs considerably between normal and inverse kinematics. Clarifying these points will help extraction of desired information from knockout reaction experiments.

Three quantities characterize the kinematics of the knockout reaction: a separation energy S_X and in-nucleus momentum $\vec{k}_F$ of the knocked-out particle and a momentum transfer q. In Ref. 1), the kinematics of (p, pX) knockout reactions is overviewed, and how S_X and $\vec{k}_F$ affects the experimental observables are discussed for normal and inverse kinematics.

Positive S_X reduces the sum of kinetic energies $T_{\text{sum}} = T_{\text{out}} + T_X$, the opening angle $\theta_{\text{open}} = \theta_{\text{out}} + \theta_X$ of the scattered proton (indicated with a subscript "out"), and the knocked out particle (a subscript X). The effect of S_X on kinematics is found to make only a minor difference between normal and inverse kinematics.

Figure 1 exhibits the distinct difference in k_{Fz} dependences between normal-[panel a)] and inverse [panel b)] kinematics $(p, 2p)$ reaction at 250 MeV, where angular dependences of the kinetic energies of the scattered proton (T_{out}) and the knocked-out particle T_X are plotted for k_{Fz} = +200 (red), +100 (orange), 0 (black), −100 (green), and −200 (blue) MeV/c. k_{Fz} is the longitudinal-to-the-beam component of $\vec{k}_F$. In normal kinematics, k_{Fz} changes the shapes of the angular distributions of kinetic energies considerably, keeping T_{sum} constant [see Fig. 10c) of Ref. 1)]. Conversely, in inverse kinematics, k_{Fz} increases or decreases, depending on its sign, and the magnitudes of the kinetic energies without essentially changing their angular distributions. This results in a tiny k_{Fz} dependence of the opening angle θ_{open} in inverse kinematics [see Fig. 14b) of Ref. 1)].

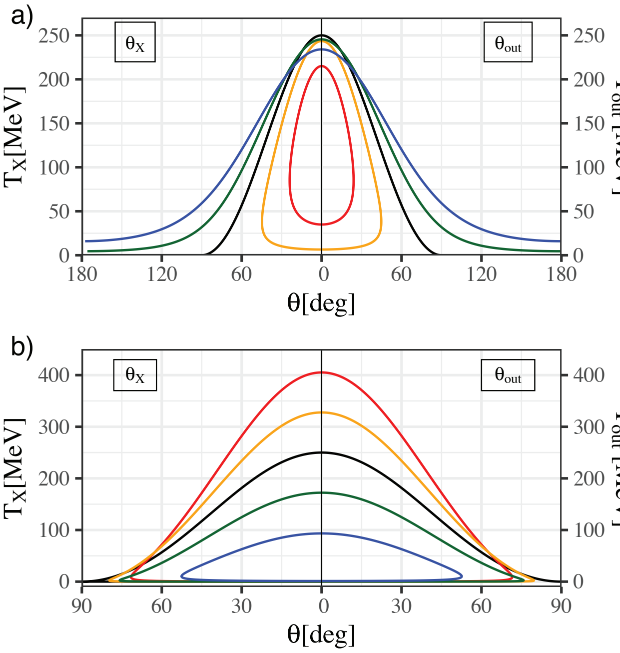

Fig. 1. k_{Fz} dependences of angular distributions of kinetic energies, T_{out} and T_X. Red, orange, black, green, and blue lines indicate calculations for k_{Fz} =+200, +100, 0, −100, and −200 MeV/c.

The constancy of T_{sum} in normal kinematics and the tiny k_{Fz} dependence of θ_{open} in inverse kinematics cause a clear difference in the independence of kinematical quantities between the two cases. In normal kinematics, T_{out} and T_X cannot be independent variables, while in inverse kinematics, θ_{out} and θ_X are not independent, which is crucial for understanding the difference between normal and inverse kinematics, leading to appropriate choices of differential variables in the description of quintuple differential cross sections for knockout reactions in two cases.

Reference

1) T. Uesaka, Prog. Theo. Exp. Phys. **2024**, 083D01 (2024).

† Condensed from the article in Prog. Theo. Exp. Phys. **2024**, 083D01 (2024)

*1 RIKEN Nishina Center

DOI:10.34448/RIKEN.APR.57-083