Systematic study of one-proton and two-proton knockout reactions by deuterium target

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Roy J. Glauber[1)] first stated that an additive law does not always hold true in nuclear reactions. He showed that the interaction cross-sections in deuteron induced reactions are smaller than the sum of those in proton- and neutron-induced reactions under the same conditions. The reduction in cross-section is due to hiding one nucleon from the other in the target nucleus. This is called an "eclipse" effect.

This effect is thoroughly investigated for the interaction cross-section but not for individual reaction channels. In this work, we investigate the deuteron and proton induced one-proton and two-proton knockout reactions for neutron-rich beams and discuss their systematic behavior.

The experiment was performed after the third SEASTAR campaign[4)] in May 2017, using the SAMURAI spectrometer and MINOS target. A cocktail beam including neutron-rich K, Ca, Sc, Ti, and V was produced through projectile fragmentation reactions of a primary ^{70}Zn beam at 345 MeV/nucleon impinging on a beryllium target. The experimental setup was the same as that in the SEASTAR experiment, except that liquid hydrogen in the target container was replaced by liquid deuterium. In the following analysis, we used the data for liquid hydrogen as well. The liquid hydrogen and deuterium targets with thicknesses of 1.1 and 2.6 g/cm^2, respectively, were used as secondary targets. Beams of ^{51}K, $^{52-54}$Ca, $^{56-57}$Sc, $^{58-60}$Ti, and $^{61-62}$V with an initial energy of ~240 MeV/nucleon lost their energies by ~90 MeV/nucleon in the target. Therefore, the cross-sections evaluated in this work are averaged over the energy range. The secondary beam and fragments were identified event by event using the ΔE-TOF-$B\rho$ method.

The systematic of interaction and one- and two-proton knockout reactions for the neutron-rich beams were obtained. In the data analysis, the MINOS-TPC tracking was not required and the cross-section was obtained by counting the number of relevant isotopes in the focal plane detectors of the SAMURAI spectrometer. Owing to large acceptance of the SAMURAI spectrometer, all beam particles and the products of one- and two-proton knockout reactions were collected. Figure 1 summarizes the data for the cross-section ratio of a deuteron target to a proton target plotted for nuclides in the cocktail beam. The green, blue, and red plots the represent interaction, one-, and two-proton knockout reaction cross-sections respectively. The ratios of interaction cross-sections had an almost constant value ~1.2 for all isotopes. This is qualitatively attributed to the eclipse effect as mentioned above. The ratios of one-proton knockout cross-sections had slightly larger values ~1.5. This is due to the difference in elementary processes. The cross-sections for p-n scattering were 60% larger than those for p-p scattering. Thus, the cross-section comprising deuterium and a neutron is larger than that of hydrogen. It should be to noted that the ratios of interaction and one-proton knockout reaction cross-section exhibited very small isotope dependences.

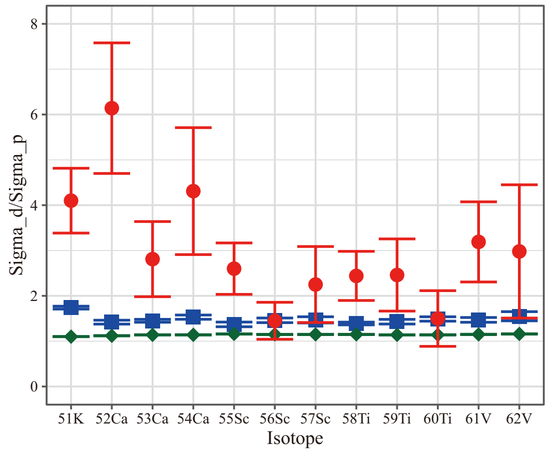

Fig. 1. Ratio(σ_d/σ_p) of cross-sections of a deuteron target to a proton target.The horizontal axis is the beam isotope. The green, blue, and red plots represent the interaction, one-proton, and two-proton knockout the reaction cross-sections respectively.

In contrast, the result of two-proton knockout cross-sections shows a significantly large deuteron/proton ratio. This value cannot be understood by the eclipse effect and/or the difference in elementary processes. We presume it originates from unknown mechanisms, which might enhance the cross-section of two-proton knockout with a deuterium target. Practically, the large values indicate the usefulness of a deuterium target in the production of neutron-rich nuclei via two-proton knockout reactions.

the data for neutron knockout reactions and channels with one and more neutron evaporation were also recorded. The systematic data can provide a comprehensive understanding of deuteron induced reactions.

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