Study of single-particle properties of nuclei and in-medium NN interaction by using \((p, 2p)\) reactions

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Abstract. We report our experimental studies on \((p, 2p)\) reactions from two kinds of view points, namely to investigate single particle properties of nuclei and to observe possible modification of NN interactions in nuclear field. Comparison of the cross section data with theoretical predictions and data of \((e, e'p)\) reaction suggests that the reaction mechanism at incident energies of around 400 MeV is simple enough to extract spectroscopic information through the \((p, 2p)\) reactions. In addition, some analyzing power data show anomaly which is not seen in cross section data and, therefore, which suggest importance of polarization studies. On the examination of the NN interaction, systematic study on analyzing powers for \(1s_{1/2}\) proton knockout has been continued. A new systematics, a \(Q\)-value dependence the analyzing power was newly observed.

1. Introduction
Nucleon knockout reactions give direct means to study single particle properties of bound nucleons. In addition to the separation energy of each nucleon orbit, distribution of the Fermi momentum relevant to the orbit is easily extracted because it is directly reflected to the kinematical dependence of cross sections. These reactions by using electron beams, namely \((e, e'p)\) reactions, have been studied intensively.[1] One of the advantages of lepton probes is that the reaction mechanism is simple because of weakness of the electromagnetic interactions. On the other hand, knockout reactions by using nucleon projectiles, such as \((p, 2p)\) reactions, have an advantage that the cross section is large. If the reaction mechanism is acceptably simple at intermediate energies, where the strength of the nuclear force shows its minimum, this large cross section allows us to perform efficient systematic studies using many target nuclei and many nucleon orbits. In addition, nowadays, it is not difficult to measure spin observables, which are quite useful to extract spin structure of the nuclear states and to examine the reaction mechanism. Here we report our recent studies on examination of this reaction as a tool for
spectroscopy, mainly by comparing experimental data with theoretical predictions and 
\((e, e'p)\) data.

Another subject for which the \((p, 2p)\) reaction gives a direct means is to study nucleon-nucleon (NN) interactions in nuclear field. Polarization studies on this reaction suggest modification of the interaction that is partially explained as an appearance of medium effects in hadronic level. [2] Our recent results of this kinds of study are also presented.

2. \((p, 2p)\) reaction as a tool for spectroscopy

In order to examine the reliability of the \((p, 2p)\) reactions as a tool for studying nuclear structure, we obtained experimental data and compared them with DWIA calculations at an incident energy of 392 MeV. Such studies have been performed at various laboratories for many years [3, 4]. The present study is distinctive from others for its variety of kinematic conditions, almost complete separation of the residual states with high resolution measurements, and accurate analyzing power measurements.

Figure 1 shows the kinematical conditions employed for the present measurements schematically. The solid lines are contour lines of the recoil momentum when the detection angles of two outgoing protons are changed and the energy of the forward outgoing proton is fixed at 250 MeV. The energy of the backward outgoing proton is also almost constant except energy carried by the residual nucleus. At the center of the figure, the recoil momentum is zero. The actual measurements of the differential cross sections and analyzing powers were performed along the dashed lines 1, 2, and 3 and a recoil-momentum dependence was deduced from the measurement along each line. Since the outgoing energies are almost fixed for these kinematics, we can use the same optical potential in DWIA calculations, which reduces ambiguities in the analysis. It is also mentioned here that the scattering angle of the elementary two body process of the \((p, 2p)\) reaction, the \(p-p\) scattering, is almost constant for the kinematics "2", and that the two-body relative energy is almost constant for the kinematics "3". As the fourth kind of recoil momentum dependence, a measurement was done at fixed angles that are the same as those for the zero-recoil condition but the energy sharing between two detected protons was changed.

A part of measured data are shown in Fig. 2 for \(^{12}\)C\((p, 2p)\) reaction leading to the ground 3/2\(^{-}\) state of the residual \(^{11}\)B nucleus. In the same figure, results of the non-relativistic DWIA and PWIA calculations are also plotted. In the case of the solid lines, optical potentials calculated by using the computer code TIMORA and FOLDER [5], based on the relativistic Hartree model and the folding model, are used. In the case of the dashed line, a global optical potentials

![Figure 1. Four kinds of kinematical conditions employed. For the kinematics 1,2, and 3, the detection energies of forward outgoing protons are fixed at around 250 MeV and two detection angles are changed along the dashed lines shown. For the kinematics 4, in contrast, the detection angles are fixed and the energy difference between two outgoing protons are changed.](image-url)
Figure 2. Experimental data for for $^{12}$C($p, 2p$) reactions leading to a 1p$_{3/2}$-hole state. The measurement was performed for four kinds of kinematical conditions indicated by encircled numbers, which correspond to those in Fig. 1. The solid lines and dashed lines are DWIA calculations with two kinds of distorting potentials and the dotted lines are PWIA calculations.

parameterized in the Dirac approach [6] are used. For both cases, the relativistic form of the optical potential was transformed to the Schrödinger equivalent form. The dotted lines are the results of PWIA calculations. As shown in the figure, all the data are reasonably well reproduced by these DWIA calculations.

The same kind of data was also obtained for $^{40}$Ca target and, again, DWIA calculations give good predictions for both of 1d$_{3/2}$-knockout and 2s$_{1/2}$-knockout. The spectroscopic factors derived from this analysis is consistent with those extracted from ($e, e'p$) analysis for both of $^{40}$Ca and $^{12}$C targets.

The single step dominance of the reaction is also seen in a comparison of separation energy spectra taken with ($p, 2p$) reaction and ($e, e'p$) reaction for $^{12}$C target. Figure 3 shows the comparison. The 5/2$^-$ at an excitation energy of 4.445MeV of the residual $^{11}$B nucleus is not a single-hole dominant state. Therefore, the cross section of the ($e, e'p$) reaction leading to this state is quite small as shown in the left panel of the figure, and, moreover, it has been estimated that the major contribution to this small cross section comes from multistep processes. In the right panel, a similar spectrum taken with ($p, 2p$) reaction is given. The cross section leading to the same state is also very small, compared with other single-hole dominant states, which imply that the multistep contribution in ($p, 2p$) reactions at this energy is also small as in the case of the ($e, e'p$) reaction.

These results show that the reaction mechanism at this energy is simple enough and this ($p, 2p$) reaction has an ability to be used as a tool to study nuclear structure.

Contrary to the data in Fig. 2, where the residual state is expected to be close to a simple single-hole state, the $^{12}$C($p, 2p$) reaction leading to the second 3/2$^-$ state of the residual $^{11}$B shows a different feature. The Fig. 4 shows a comparison of the experimental data and calculations. Although the experimental cross-section data give values close to the DWIA
Figure 3. Separation energy spectra obtained by a \((e, e'p)\) reaction (left) and a \((p, 2p)\) reaction (right). The yields of \(5/2^-\) states at an excitation energy of 4.445 MeV for the \((p, 2p)\) reaction is as small as that for the \((e, e'p)\) reaction, which shows that the multistep contribution is small enough even for the former reaction at this energy.

prediction for knockout from a \(p\)-shell orbit, the \(A_y\) data show a distinctly different angular dependence from the DWIA calculations and from the experimental values shown in Fig. 2. This imply that the structure of this residual state is not single-hole dominant. At the same time, this comparison shows the importance of the polarization measurement and suggests a possibility that new information on reaction mechanism or nuclear structure can be extracted.

3. Study of NN interaction in medium using \((p, 2p)\) reactions
Another interesting topic accessible by \((p, 2p)\) reactions is to investigate modification of the NN interaction in nuclear field, which may reflect possible medium effects on hadrons properties. For this purpose, proton knockout reactions from the \(s_{1/2}\)-orbit have been studied. Figure 5 shows experimental data of this reaction for \(A_y\), \(P\), and three spin-transfer coefficients for three kinds of target nuclei, as well as the free \(p-p\) scattering, at 392 MeV. The data are plotted as functions of the effective mean density.[7] It is clear from this figure that the \(A_y\) and \(P\) shows distinct decreasing function with the mean density. This strong density dependence is not reproduced by conventional PWIA and DWIA calculations. On the other hand, as shown in the figure, spin-transfer coefficients are well reproduced by these calculations. From the fact that existing density-dependent interactions in the non-relativistic framework do not explain this density dependence at all and that a model calculation, in which nuclear medium effect in hadron level is taken into account, predicts the similar density dependence of \(A_y\) [8], existence of some medium effect is suggested, although no calculations reproduce all of those polarization observables consistently.

Figure 4. Experimental data for \(^{12}\text{C}(p,2p)\) leading to the second \(3/2^-\) state of residual \(^{11}\text{B}\) nucleus. The kinematics "1" is used. The solid (Dotted) lines are a DWIA (PWIA) calculation in which a \(1p_{3/2}\)-knockout is assumed. The dot-dashed line in the \(A_y\)-panel is a DWIA result for \(1p_{1/2}\)-knockout.
On the reaction mechanism, namely on the contribution of the multistep processes, we have examined through several evidences. Since the detail is described in Ref. [9], only a brief summary is given here as follows.

- From the shape of spectra for $1p_{1/2}$ knockout from $^{12}$C target, contributions of multistep processes were roughly estimated. The estimated contribution is only a few percent at the cross section peak, but about a half at a tail region. After subtraction of this contribution from measured yields, the recoil-momentum dependence of the cross section was well reproduced by a DWIA calculation.

- $^{40}$Ca$(p, p')$ cross section was measured for a wide range of kinematical conditions and compared with a calculation based on a hybrid model.[10] The calculation reproduced the experimental data within factor two for whole region and contribution of the pre-equilibrium processes was deduced to be about 25% for the $1s$-knockout region and 10% for the $1p$-knockout region. A less ratio is expected for a lighter target as $^{12}$C.

- As shown in Fig. 5, density-dependent discrepancies between experimental data and IA calculations are observed only for $A_y$ and $P$. If contribution of the multi-step processes, which are likely to be less spin dependent, causes the reduction of these observables, $D_{NN}$ should also be reduced. These data show that the discrepancies are not dominantly caused by a mixture of such processes.

- We measured the polarization of the same reaction at 1 GeV and obtained essentially the same result, density dependent reduction from IA prediction, for both of forward and backward outgoing protons.[11] Moreover, the reduction rate is also similar as that at 392 MeV although contribution of the multistep processes is expected to be energy dependent.

Recently, we extend our experimental work to various light targets in $s$-shell and $p$-shell nuclei, in order to clarify the reason of these reductions. In the case of three targets shown in Fig. 5, higher mean density corresponds to larger separation energy of the knocked-out proton and it is difficult to discriminate density effect from possible off-shell effect caused by finite $Q$-value of the reaction. But in the case of $^4$He target, for example, the central density is estimated to be almost twice of the saturation density while the separation energy is smaller than the $^6$Li case.
Figure 6. Analyzing power for \((p, 2p)\) reactions corresponding to \(1s_{1/2}\) knockouts on light nuclei. The detection angle of forward outgoing protons is fixed at 25.5 degree. The angles of backward outgoing protons and energies of both protons are set so that the zero-recoil condition is fulfilled. The same data are plotted as functions of effective mean density and separation energy.

Figure 6 shows experimental data for \(A_y\), plotted as functions of effective mean density (left) and separation energy (right). As seen in the figure, the data are better aligned in the right panel, which means the separation energy, or Q-value, may be a key parameter which characterize the \(A_y\) reduction seen in the quasi-free scattering. Analysis of this result is in progress.

4. Summary
The nucleon knockout reaction at several hundred MeV was studied. Comparisons of the experimental data and DWIA calculations show that the reaction mechanism is simple enough to investigate the nucleon bound states and the NN interactions in nuclear field. In particular, it is emphasized that polarization observables play important roles in this kind of job, examination of the reaction mechanism or to extract information on nuclear medium effects. Recent progress in experimental technique allows us high resolution and low background measurements and polarization measurements including spin transfers. Fruitful information will be extracted from these new generation data.

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