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Study of Nucleon Quasi-Free Scattering and in-Medium NN Interaction

T. Noro

Department of Physics, Kyushu University, Fukuoka 812-8581, Japan

Abstract.

The proton quasifree scattering has been studied at an incident energy of 392 MeV. At this energy, the experimental data show that the reaction is single-step dominant and gives a useful tool to study single particle states of target nuclei. The reaction is also useful for studying NN interactions in nuclear field. Present status of the studies, from both view points, are presented. In addition, a discussion is also given on non-trivial breaking of an equality between analyzing power and induced polarization for $(p, 2p)$ reactions, which is caused by a relativistic effect.

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 directly reflected to the cross sections of these reactions. These reactions by using electron beams, namely $(e, e'p)$ reactions, have been studied intensively by using electron accelerators at intermediate energies. [1] One of the advantages of this reaction 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. At intermediate energies, the reaction mechanism is expected to be reasonably simple even for these nucleon induced reactions. And thus the 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 for this reaction, because of existence of high intense polarized beams and also owing to large cross sections. These observables are quite useful to extract spin structure of the nuclear states and to examine the reaction mechanism. In the next section, our studies from a view point, for investigating nuclear structure, are presented. More specifically, our experimental results on the $(p, 2p)$ reaction at an incident energy of 392 MeV are shown and compared with theoretical predictions for various kinematical conditions. Discussions are also given on advantage of studies with spin observables.

Another subject for that the $(p, 2p)$ reaction gives a direct means is to study nucleon-nucleon (NN) interactions in nuclear field. Recent polarization studies on this reaction suggest modification of the interaction that is partially explained as an appearance of medium effects in hadronic level. [2] For this kind of study, trivial effects such as a multistep effect and a nuclear distortion effect, are needed to be well estimated and information behind those disturbances is required to be extracted reliably. Practically, it is essentially important to examine reliability of DWIA applications, where single-step mechanism is assumed, to this reaction. In the Section 3, studies from this point of view are presented and a summary of examination of the reaction mechanism is also given.

As the third point, we turn our attention to symmetry breaking observed in this reaction, such as an equality between the analyzing power A_y and induced polarization P. Even though the breaking is allowed in principle in the case of $(p, 2p)$ reactions it is practically negligible in theoretical predictions with the nonrelativistic framework. We show, in the Section 4, that a relativistic calculation gives significant amount of the breaking. This may be an additional examination to test reliability of the relativistic treatment.

2 Study of $(p, 2p)$ Reactions Leading to Hole States Close to the Fermi Surface

In order to examine the reliability of the $(p, 2p)$ reactions as a tool to study 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 because of 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 a contour 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, because the residual state, therefore the Q-value as well, is fixed. At the center of the figure, the recoil momentum is almost 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 de-

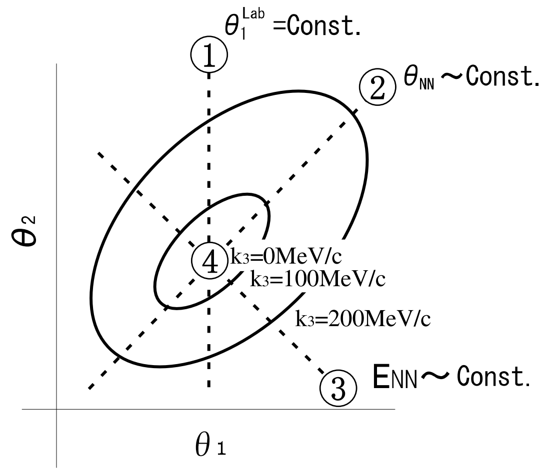

Figure 1. Four kinds of kinematical conditions employed. For the kinematics 1, 2, and 3, the detection energies of forward outgoing protons are fixed at around 250 MeV and two detection angles are changed along the dashed lines shown. For the kinematics 4, in contrast, the detection angles are fixed and the energy difference between two outgoing protons are changed.

duced from the measurement along each line. Since the outgoing energies are almost fixed for these kinematics, we can use the same optical potential in the DWIA calculations, which reduces ambiguities in the analyses. 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 Figure 2. The differential cross sections and analyzing powers of the ^{12}C$(p, 2p)$ reaction leading to the $1/2^-$ and $3/2^-$ states of the residual ^{11}B nucleus for the four kinds of kinematics are plotted as functions of the recoil momentum. In the same figure, results of 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, based on the relativistic Hartree model and the folding model, are used. In the case of the dashed line, a global optical potentials parameterized in the Dirac approach 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.

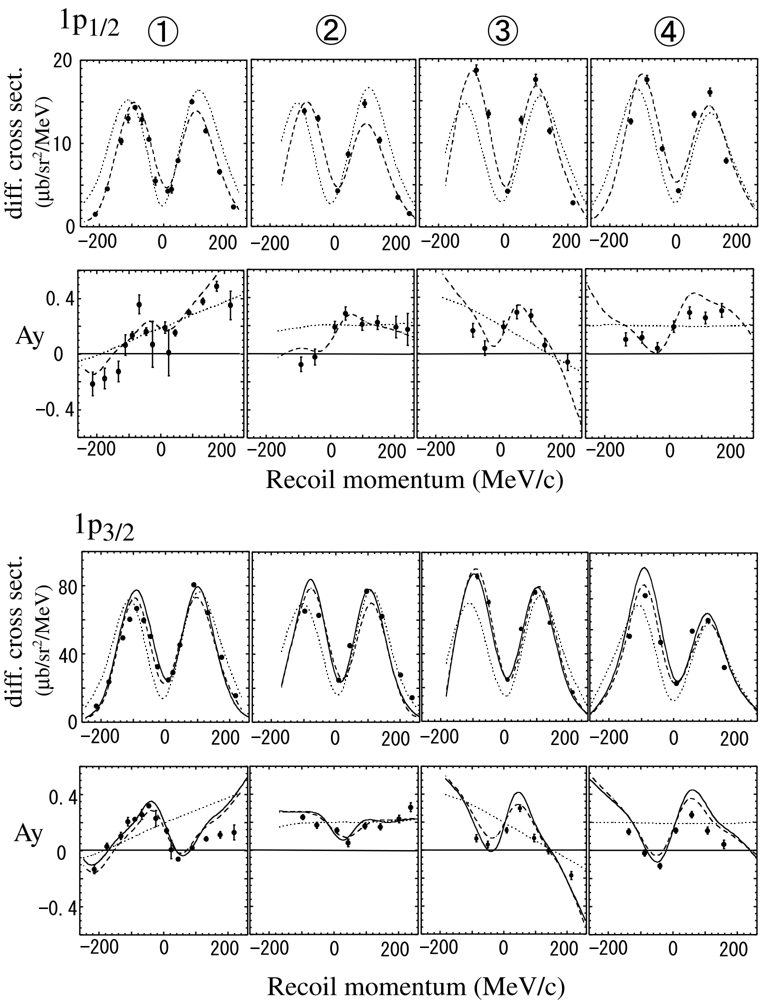

Figure 2. Experimental data for for ^{12}C($p, 2p$) reactions leading to the $1\mathrm{p}_{3/2}$- and $1\mathrm{p}_{1/2}$-hole states. The measurement was performed for four kinds of kinematical conditions indicated by encircled numbers. See the text for the details of the kinematics. The solid lines and dashed lines are DWIA calculations with two kinds of distorting potentials and the dotted lines are PWIA calculations.

As shown in the figure, all the data are reasonably well reproduced by DWIA calculations. This shows that the reaction mechanism is simple enough and this reaction at this energy has an ability to be used as a tool to study nuclear structure. Note that a clear difference between the analyzing powers of the $1\mathrm{p}_{1/2}$-

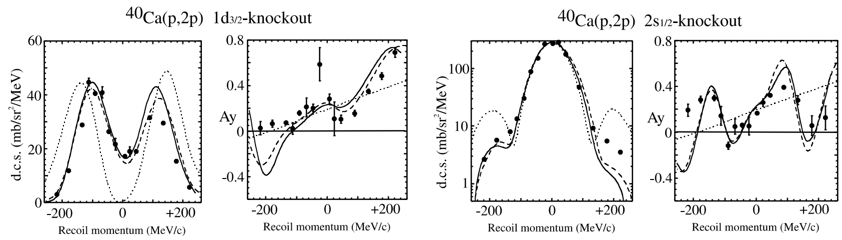

Figure 3. Experimental data for for ^{40}Ca$(p, 2p)$ reactions leading to the $1d_{3/2}$- and $2s_{1/2}$-hole states. The data for the kinematics "4" are shown. See the caption of Figure 2.

knockout and $1p_{3/2}$-knockout exists. Even though the difference does not show anti-phase pattern observed at 200 MeV [5], this j-dependence confirms an importance of spin observables in this reaction.

The same kind of data was also obtained for ^{40}Ca targets in the recent study and a part of the data are shown in Figure 3. Again, DWIA calculations give good predictions for both of $1d_{3/2}$-knockout and $2s_{1/2}$-knockout, except a limited region around $q \sim$-200 MeV/c. The spectroscopic factors derived from this analysis is consistent with those extracted from $(e, e'p)$ analyses for both of ^{40}Ca and ^{12}C targets.

Contrary to these, where the residual states are expected to be close to simple single-hole states, the ^{12}C$(p, 2p)$ reaction leading to the second $3/2^-$ state of the residual ^{11}B shows a different feature. The Figure 4 shows a comparison of the experimental data and calculations. Although the experimental cross-section data give values close to the DWIA 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 Figure 2. This imply that the structure of this residual state is not single-hole dominant. At the same time, this comparison shows an 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 topics 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 five spin-transfer coefficients for three kinds of target nuclei, as well as the free p–p scattering, at an incident energy of 392 MeV. The data are plotted as functions of the effective mean density. [6] It is clear from this figure that the A_y and P shows distinct decreasing function with the mean den-

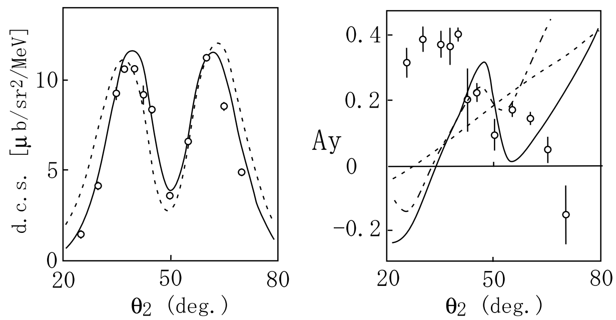

Figure 4. Experimental data for ^{12}C$(p, 2p)$ leading to the second $3/2^-$ state of residual ^{11}B nucleus. The kinematics "1" is used. The solid (Dotted) lines are a DWIA (PWIA) calculation in which a $1p_{3/2}$-knockout is assumed. The dot-dashed line in the A_y-panel is a DWIA result for $1p_{1/2}$-knockout.

sity. This strong density dependence is not reproduced by conventional PWIA and DWIA calculations. On the other hand, as shown in the figure, almost all of spin-transfer coefficients are well reproduced by these calculations. From the fact that existing density-dependent interactions in the nonrelativistic 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 [7], existence of some medium effect is suggested, although no calculations reproduce all of those polarization observables consistently.

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. [8], 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 and subtracted from the integrated differential cross section for whole of broad $1s_{1/2}$ bump. Deduced recoil-momentum dependence of the cross section was well reproduced by a DWIA calculation and the multistep contribution is only a few percent in the region where the knockout cross section is maximum.

- ^{40}Ca$(p, p'p'')$ cross section was measured for a wide range of kinematical conditions and compared with a calculation based on a hybrid model. [9] The calculation reproduced the experimental data within factor two for whole region and contribution of the preequilibrium 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.

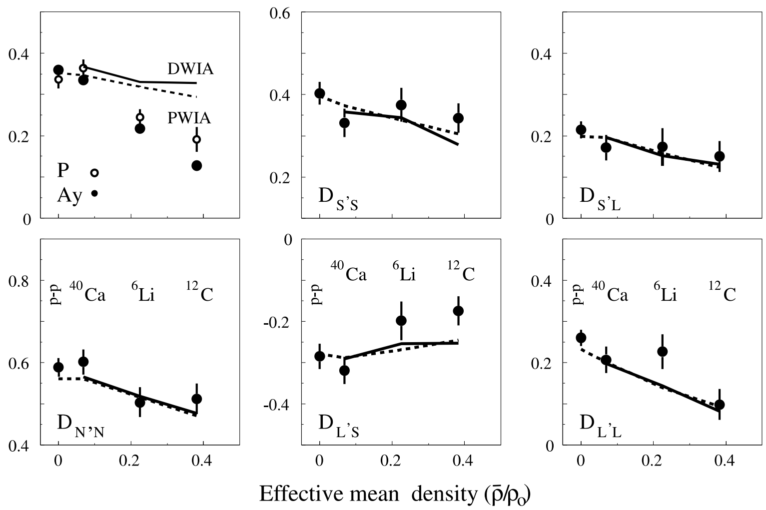

Figure 5. Seven kinds of polarization observables for $(p, 2p)$ reactions at 392 MeV. The data are plotted as functions of the effective mean density defined in Ref. [6]. The solid lines are a DWIA calculation and the dotted lines show a PWIA calculation. From the fact that the differences between the two kinds of calculations are small, it is concluded that the distortion for these kinematical conditions does not play essential roles. For A_y and P, both of PWIA and DWIA calculations give practically the same values because an on-shell factorized approximation is employed.

- As shown in Figure 5, density-dependent discrepancies between experimental data and IA calculations are observed only for A_y and P. If contribution of the multistep 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. [10] Moreover, the reduction rate is also similar as that at 392 MeV although contribution of the multistep processes is expected to be energy dependent.

Quite 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 Figure 5, higher mean density corresponds to larger separation energy of a 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

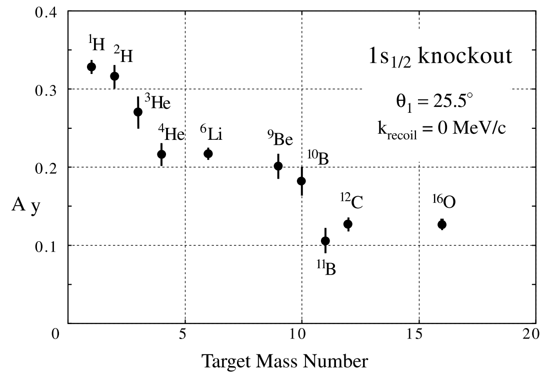

Figure 6. Analyzing power for $(p, 2p)$ reactions corresponding to $1s_{1/2}$ knockouts on light nuclei. The detection angle of forward outgoing protons is fixed at 25.5 degree. The angles of backward outgoing protons and energies of both protons are set so that the zero-recoil condition is fulfilled.

almost twice of the saturation density while the separation energy is smaller than the ^{6}Li case.

Figure 6 show a preliminary experimental data for A_y, plotted as functions of target mass number. Since the data show roughly a monotonically decreasing function of the mass number, and since the separation energy is also a monotonic function of the mass number, the A_y change with the separation energy monotonically. At least, the A_y does not seem to scale with the effective mean density derived using a simple local density assumption. Further analysis is in progress.

4 Energy Off-Shell Effect Caused by a Spin Distortion

For a p–p scattering in free space, the time reversal invariance requires that the polarization P and the analyzing power are equal. There is also an equality between two spin transfer coefficients, $D_{pq} = -D_{qp}$, where q and p are the directions of the transfered momentum and an average of incident and final momenta, respectively, in the cm system.

In the case of a $(p, 2p)$ reaction, these equalities are broken even if its reaction process is simply one step so that the NN scattering in nuclear field is the elementary process. Actually, the data in Figure 5 show a finite difference between P and A_y. The data are re-plotted in Figure 7 as a function of the $(k-k')/(k+k')$, where k and k' are the relative momenta of two protons in the initial and final channels, respectively. In the same figure, $D_{pq}+D_{qp}$ values are also plotted and again a finite experimental value is given. Here we discuss about these inequalities caused by a distortion in the Schrödinger equivalent expression of the relativistic DWIA.

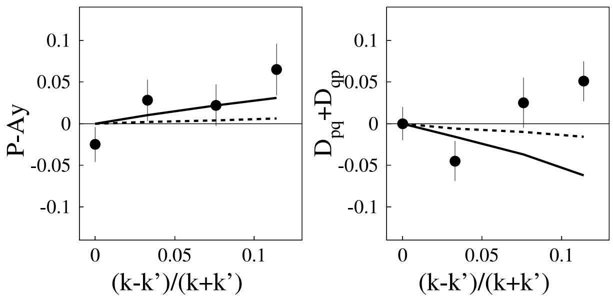

Figure 7. Experimental data and theoretical estimations for the observables which vanish for elastic NN scattering. The dashed lines show a non-relativistic distortion effect and the solid lines represents an effect of relativistic distortion.

A trivial distortion effect is given by distorting potentials which is the same as that in a non-relativistic framework. But this effect is negligible small, at least for the kinematics corresponds to these data, as shown by the dashed lines in the figure.

In the relativistic framework, another kind of distortion effect exists. It is an enhancement of the lower component of the nucleon spinor in nuclear field. In the Schrödinger equivalent expression, this effect is taken into account as modifications of effective NN amplitudes. In the expression, the t-matrix of the NN scattering in the nonrelativistic framework is equated to the Dirac-spinor matrix elements of Lorentz invariant amplitudes.

For a free NN scattering, the t-matrix is expressed with five terms as

$$t = A + B\sigma_{1n}\sigma_{2n} + C(\sigma_{1n} + \sigma_{2n}) + E\sigma_{1p}\sigma_{2p} + F\sigma_{1q}\sigma_{2q} \tag{1}$$

under assumptions of parity and time reversal invariances. Here n refers to a direction normal to the reaction plane, p and q refer to the same directions as mentioned above, and σ_1 and σ_2 are the spin operators for two nucleons. Since the lower component of the Dirac spinor is a function of the nucleon momentum as well as the effective nucleon mass, the difference of the momenta between the initial and final channels causes additional terms in the effective t matrix. Actually it is easily derived that the term

$$D(k^2 - k'^2)(\sigma_{1p}\sigma_{2q} + \sigma_{1q}\sigma_{2p})$$

appears if $k \neq k'$. This term is equivalent to the *D-term* proposed by KMT [11] and causes finite P-A_y and D_{qp}+D_{pq} values.

The value of this amplitude was estimated following a similar procedure to that proposed by Horowitz and Iqbal [12], by using a five-term approximation for the Lorentz invariant amplitudes. The result is plotted in the figure with solid lines. The plot shows that this off-shell effect causes significant deviations from zero for both of those observables. Even though the calculation gives the opposite sign for D_{qp}+D_{pq} and a refinement of the theoretical estimation will be required, the present result shows that this kind of relativistic effect is not negligible and, conversely, gives new information on reliability of the relativistic treatments of nuclear reactions.

5 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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