Exclusive Measurement of Proton Quasifree Scattering and Density Dependence of the Nucleon-Nucleon Interaction

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Differential cross sections and analyzing powers (A_y) have been measured for the proton knockout reaction from $s_{1/2}$ orbits of three kinds of target nuclei at $E_p = 392$ MeV. The A_y values are reduced from those of free proton-proton scattering and the reduction rate is found to depend on target. For the present setting, where the recoil momentum is almost zero, an averaged density seen through this reaction can be estimated and it reaches almost half of the saturation density in some cases. The reduction of A_y shows a monotonically decreasing function of the averaged density, which strongly suggests the existence of a nuclear medium effect on the nucleon-nucleon interaction. [S0031-9007(97)02312-0]

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Modification of meson and nucleon properties in the nuclear medium is one of the most interesting topics in current nuclear physics. Reduction of hadron masses in medium have been predicted as an effect of the partial restoration of chiral symmetry in nuclear matter by many authors [1–3]. From a different viewpoint, modification of the nucleon spinor in nuclear matter has also been discussed in the framework of a Dirac approach [4]. Such modification causes a density dependence of the nucleon-nucleon (NN) interaction and is expected to play an important role in nucleon induced reactions [5,6].

Exclusive measurements of nucleon quasifree scattering give a direct way to study the NN interaction in nuclei and, therefore, to study meson and nucleon properties in the nuclear medium. At an incident energy of several hundred MeV, the distorted wave approximation is expected to give proper results, and this makes it possible to compare the NN amplitude in the nuclear field with that in free space.

In the quasifree scattering of nucleons in this energy region, a reduction of the analyzing power (A_y), from that of free nucleon-nucleon scattering, has been found in inclusive measurements [7]. This reduction has been explained by a Dirac approach [4,8,9] as a modification of the effective NN amplitude caused by the enhancement of the lower component of the nucleon spinor in the nuclear medium. For exclusive measurements, the data of spin observables [10,11] have been reproduced fairly well by a relativistic distorted wave impulse approximation (DWIA) [12,13] in general. At 500 MeV, however, a distinct reduction of A_y was found for the nucleon knockout reaction, $(p,2p)$ reaction, from the 1s orbit of ^{16}O nucleus whose wave function has the bulk of its strength within the nuclear surface [14]. This reduction has not been reproduced even by the relativistic DWIA and the relationship between this fact, and the spin-orbit parts of the distorting potentials is discussed [15]. This kind of reduction is also observed at higher energies [16,17] though any selection of final state has not been performed.

In this paper, we report on our measurement of the $(p,2p)$ reaction directing attention to the nuclear density which was not explicitly estimated in the previous works. Differential cross sections and A_y have been measured for the proton knockout reaction from $s_{1/2}$ orbits of ^{6}Li, ^{12}C, and ^{40}Ca nuclei at the kinematical geometry close to zero-recoil condition. There are a number of advantages in the choice of this condition. First, the differential cross section of the $s_{1/2}$-nucleon knockout has a maximum at the zero-recoil geometry, and the reaction mechanism is expected to be simple. Second, as is mentioned in Ref. [14], a simpler relation is expected between the spin observables of the $(p,2p)$ reaction and the NN scattering, which is the elementary process of this reaction. In the case of $\ell \neq 0$ orbits, on the other hand, an effective polarization [18] of bound protons makes the relation more complex. Finally, the averaged density *seen* through this reaction can be estimated in the zero-recoil case, which will be described later in this paper.

The experiment has been performed by using a polarized proton beam of 392 MeV accelerated by the ring cyclotron at RCNP, Osaka. The pair spectrometer system, consisting of the high resolution spectrometer [Grand Raiden (GR)] [19] and the large acceptance spectrometer (LAS) [20], has been used for this measurement. The setting angles of the spectrometers and the magnetic field for GR are those corresponding to free proton-proton $(p\text{-}p)$ scattering. The acceptance angles of GR and LAS are ± 20 mrad and

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± 60 mrad, respectively, and the momentum bite of the GR is $\pm 2.5\%$. The momentum bite of LAS is wide enough to measure free p-p scattering and the $(p,2p)$ reaction simultaneously with a single field setting.

Overall energy resolution of 350 keV has been achieved, and the $1/2^+$ level of the residual ^{39}K nucleus, in the case of the ^{40}Ca target, is well separated from other major levels. An adjacent $7/2^+$ level is not separated but its contribution is estimated to be 0.3% in cross section and 1×10^{-4} in A_y, at most, by a DWIA calculation.

Experimental data are shown in Fig. 1. For the ^{40}Ca target, the full momentum bite, $\pm 2.5\%$, of GR is integrated. For the ^{6}Li and ^{12}C targets, since the final states are not discrete ones, integration of 5 MeV in the Q-value spectrum has been performed in addition to the integration for the momentum bite of GR. The A_y data for free p-p scattering is also shown by open circles. As shown in the figure, A_y of the $(p,2p)$ reaction is reduced from the free p-p value for all of the targets, and the reduction is especially evident in the case of $1s_{1/2}$ knockout from the ^{12}C target, which is consistent with the previous data [14]. It is also found from the PWIA and DWIA calculations that the angular dependence of the A_y reduction and the distinct reduction at forward angles are not explained as an effect of distortion.

Then, what is the key parameter which characterizes the A_y reduction? Here we tried to estimate the averaged density seen in this reaction in the framework of a factorized DWIA with the local density approximation.

We assume the NN t matrix depends on the nuclear density linearly as

$$t = t_0 + t_1 \rho(r),$$

where $\rho(r)$ is nuclear density at radius r. Effects of spin degrees of freedom are neglected in this estimation. Then the differential cross section of the $(p,2p)$ reaction in factorized DWIA is written as

$$\begin{aligned}\frac{d\sigma^5}{d\Omega_1\, d\Omega_2\, dE_1} &= F_k \left| t_0 \int \chi_1(\mathbf{r})^* \chi_2(\mathbf{r})^* \phi(\mathbf{r}) \chi_0(\mathbf{r})\, d\mathbf{r} + t_1 \int \chi_1(\mathbf{r})^* \chi_2(\mathbf{r})^* \rho(r) \phi(\mathbf{r}) \chi_0(\mathbf{r})\, d\mathbf{r} \right|^2 \\ &= F_k \left| t_0 \int \chi_1(\mathbf{r})^* \chi_2(\mathbf{r})^* \phi(\mathbf{r}) \chi_0(\mathbf{r})\, d\mathbf{r} \right|^2 \left\{ 1 + 2\,\mathrm{Re}\left(\frac{t_1}{t_0} \bar{\rho} \right) + \left| \frac{t_1}{t_0} \bar{\rho} \right|^2 \right\},\end{aligned}$$

where F_k is a kinematical factor, $\chi_i(r)$ and $\phi(r)$ are distorted waves of the incident ($i = 0$) and outgoing ($i = 1, 2$) particles and the bound wave function, respectively. The averaged density $\bar{\rho}$ is defined as

$$\bar{\rho} \equiv \frac{\int_0^\infty \rho(r) D(r)\, dr}{\int_0^\infty D(r)\, dr},$$

$$D(r) \equiv \int \chi_1(\mathbf{r})^* \chi_2(\mathbf{r})^* \phi(\mathbf{r}) \chi_0(\mathbf{r}) r^2\, d\Omega.$$

It is mentioned here that $\bar{\rho}$ is a complex number in general, and the second term, in the expression of the cross section, does not depend on $\bar{\rho}$ itself. For the present kinematics, however, the recoil momentum k_3 is close to zero and $\chi_1(\mathbf{r})^* \chi_2(\mathbf{r})^* \chi_0(\mathbf{r}) \sim e^{i\mathbf{k}_3\mathbf{r}}$ is expected to be almost constant. Thus $\bar{\rho}$ is close to a real value and the cross section depends on $\bar{\rho}$ linearly in the first order approximation, which is adequate unless the relative phase between t_0 and t_1 is close to 90°. This means that $\bar{\rho}$ can be used as a measure which shows the sensitivity of this reaction to the density dependent terms of the t matrix.

On the other hand, we can easily calculate the following value using a DWIA code, by eliminating a narrow part in radius from the integral step by step,

$$\begin{aligned}\delta(r_1) &\equiv F_k \frac{|t_0 \int_0^\infty D(r)\, dr|^2 - |t_0 \int_0^{r_1} D(r)\, dr + t_0 \int_{r_1+\Delta R}^\infty D(r)\, dr|^2}{\Delta R} \\ &= F_k \left(t_0 \int_0^\infty D(r)\, dr \right) (t_0 D(r_1))^* + F_k \left(t_0 \int_0^\infty D(r)\, dr \right)^* (t_0 D(r_1)).\end{aligned}$$

The second line holds under the infinitesimal limit of ΔR. Using this function as a weighting function, we can calculate

$$\begin{aligned}\frac{\int_0^\infty \rho(r) \delta(r)\, dr}{\int_0^\infty \delta(r)\, dr} &= \frac{F_k |t_0|^2 [(\int_0^\infty D(r)\, dr)(\int_0^\infty \rho(r) D(r)\, dr)^* + (\int_0^\infty D(r)\, dr)^* (\int_0^\infty \rho(r) D(r)\, dr)]}{2F_k |t_0|^2 (\int_0^\infty D(r)\, dr)(\int_0^\infty D(r)\, dr)^*} \\ &= \mathrm{Re}(\bar{\rho}).\end{aligned}$$

Again, $\bar{\rho}$ is close to a real value, and we can use the left-hand side to estimate the averaged density which the cross section depends on.

DWIA calculations for this estimation, as well as the calculation in Fig. 1, were performed by using the computer code THREEDEE [21]. In order to avoid inconsistencies among the parameters required in the calculations, we used a

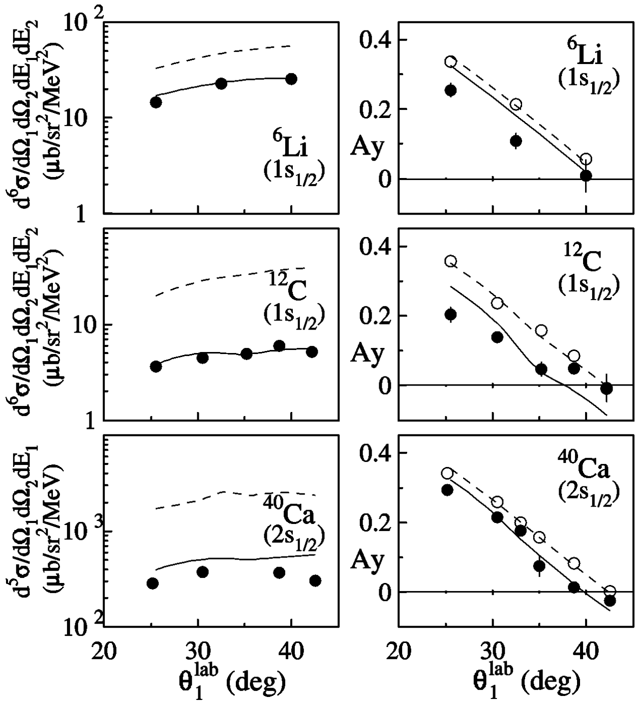

FIG. 1. Experimental data for $(p, 2p)$ reaction (closed circles) and free p-p scattering (open circles), which are simultaneously measured by using hydrogen contaminations. The abscissa is the detection angle of forward outgoing protons in the laboratory system. The solid (dashed) lines show DWIA (PWIA) calculations in the nonrelativistic framework. The effects of finite solid angles and finite momentum bites of the spectrometers are included in the calculation by using the Monte Carlo method. The spectroscopic factor for ^{40}Ca is taken from Ref. [23]. Since the widths of the $1s_{1/2}$ states are not taken into account in the calculations, the DWIA cross sections for ^{12}C and ^{6}Li are normalized to the experimental data.

result of the Dirac Hartree calculations [22]. The baryon densities obtained are used for $\rho(r)$ and the Schrödinger-equivalent potentials derived by using the scaler and vector densities are used as the distorting potential. The wave functions of s-orbits used are those of the upper component obtained in the Dirac Hartree calculation.

Figure 2 shows the function $\delta(r)$, which represents the contribution to DWIA cross sections. The density distribution, $\rho(r)$, is also plotted. Even though $\delta(r)$ is concentrated in the surface region of $\rho(r)$ for each target, the averaged density amounts to 0.09 fm^{-3} in the case of $1s_{1/2}$ knockout from ^{12}C target. This value amounts to half of the nuclear saturation density and 43% of the density at the center of the ^{12}C nucleus.

In Fig. 3, the A_y data for the scattering angle of 25.5° are plotted as a function of the averaged density obtained above. It is clear that the A_y data decrease with the density monotonically and the DWIA calculation does not reproduce this reduction. This strongly suggests the existence of a density dependence in the effective NN interaction in the nuclear field.

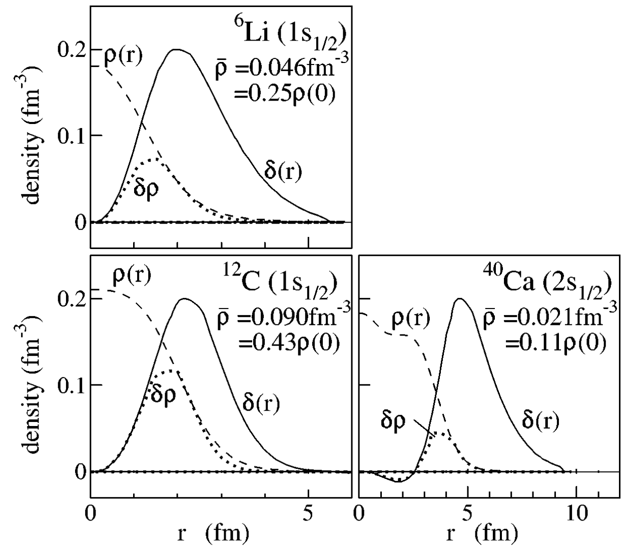

FIG. 2. Contribution to the DWIA cross section, $\delta(r)$, as a function of radius parameter. The nuclear density given by relativistic Hartree calculations, $\rho(r)$, and the product of both functions are also plotted. The ordinate is given for $\rho(r)$ and the other two functions are plotted in arbitrary unit. The ratio of the integration of $\delta(r)\rho(r)$ and that of $\delta(r)$ gives the averaged density $\bar{\rho}$ seen through this reaction.

It should be pointed out here that the values of the averaged density obtained are model dependent and parameter dependent. Proper "density," such as baryon density, scalar density, etc., should be selected depending on the kind of medium effect considered. Consistency between

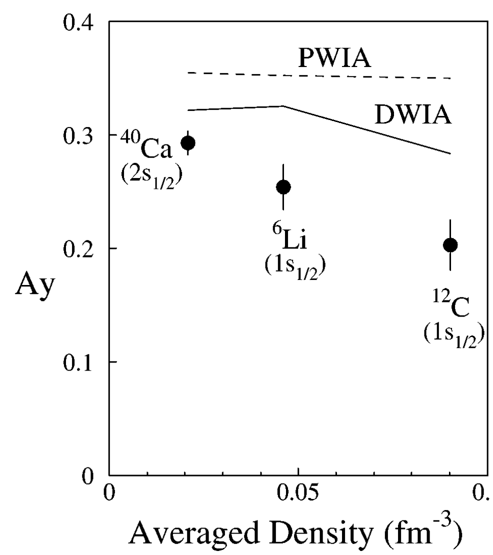

FIG. 3. Analyzing power for $\theta_1 = 25.5°$, a part of data in Fig. 1, is plotted as a function of the averaged density defined in the text. The density dependence of A_y is not reproduced by DWIA and PWIA calculations. The calculations shown are the results with the final-state prescription of the on-shell approximation and the initial-state prescription gives 0.02 larger values for both of DWIA and PWIA results in the case of ^{12}C target.

the density distribution, optical potential, and bound wave function is also important. In the case of ^{12}C, for instance, the averaged density ranges from 35% to 47% of the density at the origin depending on the choice of parameters. In either case, however, a much smaller value is obtained for ^{40}Ca and a middle value is given for ^{6}Li. Thus we can conclude that it is possible to see the nuclear interior region with considerable density by picking up the deeply bound $1s$ state and also possible to extract the density dependence by a systematic study of different s states of different target nuclei. It is also noticed that the distortion effect to A_y is not significant in the present kinematics, and this $\bar{\rho}$ estimation, which is appropriate when the mixture of spin states in distorted waves is negligible, is expected to give a reasonable result.

The reduction of A_y has been discussed in two kinds of theoretical approaches. By following the approach by Horowitz's group [4,8], about a 40% reduction of A_y is predicted in the case of the ^{12}C data of Fig. 3, where the averaged density is about 50% of the saturation density. On the other hand, Krein *et al.* [6] have suggested that the reduction of meson masses and coupling constants cause the modifications of spin observables of quasifree scattering. If effective masses and coupling constants for saturation density are set to the values assumed in their work, the A_y are reduced by about 45% when the density is 50% of the saturation density. Thus each of these approaches reproduce, qualitatively at least, the A_y reduction. It will be required to measure other spin observables and to compare them with theories to clarify the origin of the A_y reduction.

In summary, we have measured the differential cross section and analyzing power for the $(p, 2p)$ reaction of $s_{1/2}$ knockout at an incident energy of 392 MeV with an energy resolution of 350 keV. The kinematical conditions chosen are close to those for the free p-p scattering, where the $(p, 2p)$ cross section is a maximum and a single step process is expected to be dominant. The analyzing power shows some reduction, which depends on the target and knocked-out orbit, from the free values.

It is an advantage of the present geometry that the averaged density seen through this reaction can be estimated for each target under the assumptions of local density approximation and factorized DWIA. The averaged density estimated is low for $2s_{1/2}$ knockout but is almost half of the saturation density for $1s_{1/2}$ knockout from ^{12}C. The dependence of the A_y reduction on this averaged density strongly suggest that the existence of some medium effect on the NN interaction in nuclei.

It should be stressed here that the remarkable density achieved by picking up a $1s$ nucleon is not restricted to the quasifree scattering. It is applicable to any reaction started by two nucleon collisions. For instance, meson creation reactions preceded from a collision of an incident nucleon and a $1s$ nucleon will give a good tool to study the properties of real mesons in the nuclear medium.

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[1] G. E. Brown and M. Rho, Phys. Rev. Lett. **66**, 2720 (1991).
[2] R. J. Furnstahl, D. K. Griegel, and T. D. Cohen, Phys. Rev. C **46**, 1507 (1992).
[3] T. Hatsuda, Nucl. Phys. **A544**, 27c (1992).
[4] C. J. Horowitz and M. J. Iqbal, Phys. Rev. C **33**, 2059 (1986).
[5] G. E. Brown, A. Sethi, and N. M. Hintz, Phys. Rev. C **44**, 2653 (1991).
[6] G. Krein *et al.*, Phys. Rev. C **51**, 2646 (1995).
[7] J. A. McGill *et al.*, Phys. Lett. **134B**, 157 (1984).
[8] C. J. Horowitz and D. P. Murdock, Phys. Rev. C **37**, 2032 (1988).
[9] G. C. Hillhouse and P. R. De Kock, Phys. Rev. C **49**, 391 (1994).
[10] P. Kitching *et al.*, in *Advances in Nuclear Physics*, edited by J. W. Negele and E. Vogt (Plenum, New York, 1985), Vol. 15, p. 43, and references therein.
[11] W. J. McDonald *et al.*, Nucl. Phys. **A456**, 577 (1986).
[12] E. D. Cooper and O. V. Maxwell, Nucl. Phys. **A493**, 468 (1989); O. V. Maxwell and E. D. Cooper, Nucl. Phys. **A513**, 584 (1990); **A565**, 740 (1993).
[13] Y. Ikebata, Phys. Rev. C **52**, 890 (1995).
[14] C. A. Miller *et al.*, in *Proceedings of the 7th International Conference on Polarization Phenomena in Nuclear Physics, Paris, 1990* (Editions de Physique, Les Ulis, France, 1990), C6-595.
[15] O. V. Maxwell and E. D. Cooper, Nucl. Phys. **A574**, 819 (1994).
[16] J. Bystricky *et al.*, Lett. Nuovo Cimento **40**, 466 (1984).
[17] C. Ohmori *et al.*, Phys. Lett. B **243**, 29 (1990).
[18] G. Jacob *et al.*, Phys. Lett. **45B**, 181 (1973).
[19] M. Fujiwara *et al.*, in *Proceedings of the 5th French-Japanese Symposium on Nuclear Physics, Dogashima, 1989* (University of Tokyo, Tokyo, 1989), p. 348.
[20] N. Matsuoka *et al.*, RCNP Annual Report 1992, p. 174.
[21] N. S. Chant and P. G. Roos, Phys. Rev. C **27**, 1060 (1983).
[22] C. J. Horowitz, D. P. Murdock, and B. D. Serot, in *Computational Nuclear Physics*, edited by K. Langanke, J. A. Maruhn, and S. E. Koonin (Springer-Verlag, Berlin, Heidelberg, 1991), Vol. 1, p. 129.
[23] P. Doll *et al.*, Nucl. Phys. **A263**, 210 (1976).