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Analyzing powers for exclusive $1s_{1/2}$ proton knockout from light nuclei

T. Noro,[1,*] T. Yonemura,[1] S. Asaji,[1] N. S. Chant,[2] K. Fujita,[3] Y. Hagihara,[1] K. Hatanaka,[3] G. C. Hillhouse,[1,4] T. Ishida,[1] M. Itoh,[3] S. Kishi,[5] M. Nakamura,[5,†] Y. Nagasue,[1] H. Sakaguchi,[5] Y. Sakemi,[3] Y. Shimizu,[3] H. Takeda,[5,‡] Y. Tamesige,[3] S. Terashima,[5] M. Uchida,[5] T. Wakasa,[1] Y. Yasuda,[5] H. P. Yoshida,[3,§] and M. Yosoi[5]

[1]*Department of Physics, Kyushu University, Fukuoka 812-8581, Japan*

[2]*Department of Physics, University of Maryland, College Park, Maryland 20742, USA*

[3]*Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan*

[4]*Department of Physics, University of Stellenbosch, Stellenbosch 7600, South Africa*

[5]*Department of Physics, Kyoto University, Kyoto 606-8502, Japan*

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Analyzing power data are reported for exclusive proton-induced proton knockout from the $1s_{1/2}$ states of 10 target nuclei ranging from ^{2}H to ^{19}F for an incident energy of 392 MeV. Compared to free proton-proton scattering, the data are significantly suppressed, the amount of suppression increasing monotonically as a function of increasing separation energies for the knocked-out protons. It is also possible to consider that this suppression increases monotonically as a function of the increasing effective mean density for most of the target nuclei, but data for ^{3}He and ^{4}He targets clearly deviate from such systematic change. The data are compared to model predictions based on the nonrelativistic and relativistic distorted-wave impulse approximation. Both relativistic plane wave model and a nonrelativistic distorted-wave model incorporating a relativistic correction associated with an effective nucleon mass predict a significant suppression of the analyzing power, but the magnitude of the suppression is not sufficient to explain the experimental data. However, a relativistic distorted wave model predicts values that are closer to the data, but the result is inconclusive in this work since recoil corrections are neglected.

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Exclusive proton-induced proton knockout reactions at intermediate energies provide one of the most direct means to investigate the single-particle properties of nuclei as well as to study the influence of the nuclear field on the free nucleon-nucleon (*NN*) interaction. Unpolarized differential cross sections for exclusive $(p, 2p)$ reactions strongly reflect the momentum dependence of the single-particle state associated with the knocked-out proton, and the recoil-momentum dependence of the cross section is reasonably well reproduced by models based on the impulse approximation [1,2]. However, there is a long standing problem in the $(p, 2p)$ analyzing power A_y for $1s_{1/2}$ knockout from various nuclei, whereby the data are significantly reduced from the model predictions based on the *NN* interaction in free space, as described in the following. Since proton knockout from $1s_{1/2}$ states is expected to emphasize the contribution of the nuclear interior to the cross section, these reactions are ideal for studying the influence of the surrounding nuclear medium on the free *NN* interaction.

The suppression of A_y in exclusive measurements was first observed at TRIUMF for the ^{16}O$(p, 2p)^{15}$N reaction at an incident energy of 500 MeV [3,4]. The same kind of suppression in $1s_{1/2}$-proton knockout was also observed at RCNP for ^{6}Li and ^{12}C target nuclei and a small suppression for $2s_{1/2}$ knockout from ^{40}Ca has also been detected [5]. In the latter work, an effective mean density, which reflects the contribution of the nuclear interior to this reaction, was introduced, and the A_y suppression was shown to increase monotonically with increasing mean density. Recently, a similar suppression was observed at 1 GeV for the polarization P, instead of A_y [6,7]. This result indicates that such suppression is a general feature of $1s_{1/2}$-proton knockout, independent of the incident and outgoing energies, and that multistep processes cannot alone account for the effect. In addition to $1s_{1/2}$ knockout, a South African group has reported a similar A_y result at an incident energy of 202 MeV for $3s_{1/2}$-proton knockout from a ^{208}Pb target [8].

To date no theoretical model has succeeded in reproducing these data for $1s_{1/2}$ knockout quantitatively. The TRIUMF data were analyzed with a nonrelativistic distorted-wave impulse approximation (DWIA) model including density-dependent corrections to the *NN* interaction as well as with a relativistic DWIA model using a density-independent *NN* interaction [4,9]. Some of those showed significant reduction of A_y compared to the nonrelativistic DWIA calculations employing the *NN* interaction in free space, but the reduction amount was much smaller than the experimentally observed reductions. A recent relativistic DWIA prediction has succeeded in reproducing the suppressed A_y for the aforementioned $3s_{1/2}$ knockout at 202 MeV [10], but no $1s_{1/2}$-knockout data have been reported for this target. Regarding medium modifications of the *NN* force, Krein *et al.* demonstrated a possible mechanism for the suppression of A_y through the introduction of medium-modified meson masses and coupling

*Electronic address: noro@nucl.phys.kyushu-u.ac.jp.

†Present address: Wakayama Medical University, Wakayama 641-8509, Japan.

‡Present address: Institute of Physical and Chemical Research (RIKEN), Wako 351-0198, Japan.

§Present address: Research and Development Center for Higher Education, Kyushu University, Fukuoka 810-8560, Japan.

constants [11] via the Rho-Brown scaling law [12], though no quantitative comparison with experimental data was achieved.

Up until now, measurements of A_y or P for $1s_{1/2}$-proton knockout have been performed only for a limited number of target nuclei. In the present study, we extend these measurements to include 10 target nuclei ranging from ^{2}H to ^{19}F (i.e., ^{2}H, ^{3}He, ^{4}He, ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, ^{11}B ^{16}O, and ^{19}F). One of our main aims is to perform a systematic study of the A_y-suppression problem for $1s_{1/2}$-state proton knockout. Among these target nuclei, the ^{4}He nucleus is especially interesting since the nuclear density of the central region of this nucleus is thought to be remarkably high [13,14]. Indeed, if the A_y reduction is an indication of some medium modification of the *NN* interaction, it is expected to be density dependent, and the A_y value for this target is expected to be more suppressed than for the other targets, in the light of the large mean density sampled by $1s$ knockout from this target, as will be shown in the following. We also intend to identify the key parameter that characterizes the A_y suppression from a systematic study of the experimental data. As already mentioned, it is known that the relativistic calculations explain a part of such A_y suppression. It is also our intention to compare the experimental data with various calculations including relativistic effects.

The measurement was performed at RCNP using a polarized proton beam at a bombarding energy of 392 MeV. The beam polarization was continuously monitored using a polarimeter system with a CH_2 target. The average polarization was typically 70%. Exclusive proton-induced proton-knockout measurements were performed for the ten target nuclei. In addition, free proton-proton (p-p) scattering data were also taken. Both ^{2}H and ^{4}He were prepared as cooled gas targets at temperatures of about 30 and 15 K, respectively, using a target system developed for a liquid H_2 target [15]. Proton-proton scattering off the window foil of this target was used to extract p-p scattering data. The ^{3}He target was prepared as a gas target within an aluminum cylinder at room temperature. Data for ^{16}O were obtained from the difference of yields from ^{6}LiO and ^{6}Li targets. Data for ^{19}F were deduced from a combined analysis of data taken for LiF, ^{6}Li, and ^{7}Li targets.

The outgoing protons were momentum analyzed with a two-arm spectrometer system consisting of Grand Raiden (GR) [16] and the Large Acceptance Spectrometer (LAS) [17]. The setting angle of GR was fixed at 25.5 degrees. The angle of LAS and the magnetic fields of both spectrometers were set so that the recoil momentum of the residual nucleus was approximately zero for each of $1s_{1/2}$-knockout reactions with finite Q value. Note that the latter setting is different from that used in Ref. [5], where the angle of LAS and the magnetic field of the spectrometers were set at values corresponding to the kinematics for free p-p scattering. The energy bite of GR was limited to ± 4 MeV in data processing and that of LAS was wide enough to cover the region of interest. Collimators with opening angles of ± 20 mr wide and ± 30 mr high for GR and ± 50 mr wide and ± 45 mr high for LAS were placed at the front of each spectrometer.

Figure 1 shows typical separation-energy spectra. The accidental coincidence events were estimated using coincidence events between adjacent beam bunches and were subtracted at each stage of the data reduction. The true-to-accidental ratios

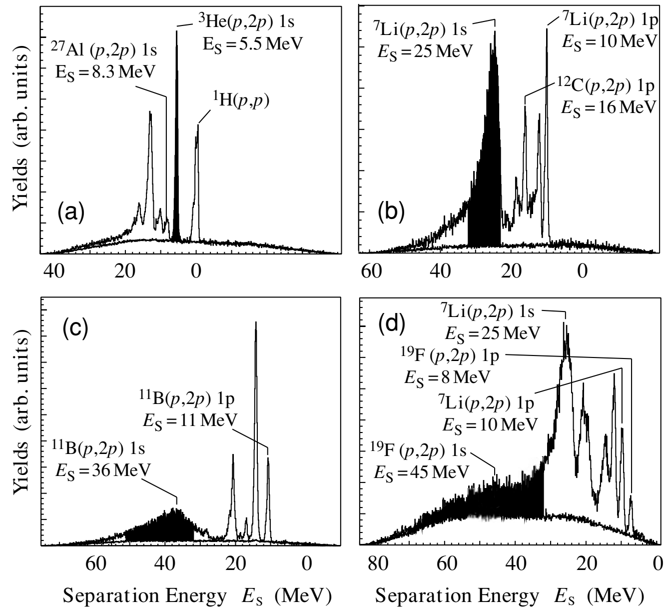

FIG. 1. Typical separation energy spectra for $(p, 2p)$ reactions from (a) ^{3}He, (b) ^{7}Li, (c) ^{11}B, and (d) LiF targets. Accidental coincidence events estimated by coincidence triggering between adjacent beam bunches are indicated by the lines underneath the spectra. The shaded areas underneath the peaks correspond to $1s_{1/2}$ knockout, which has been corrected for accidental coincidences. In the case of the LiF (d), yields from Li isotopes were estimated in separate runs using ^{6}Li and ^{7}Li targets and were subtracted in the process of data reduction to extract the yields for ^{19}F.

were better than 10 for a few of the lightest targets and about 0.25 for ^{19}F. With the exception of the ^{3}He and ^{4}He targets, the residual states corresponding to $1s_{1/2}$-nucleon knockout are not discrete states and the spectra show bumps with finite widths. We integrated over the major part of each bump, as shown in Fig. 1. The experimental results, as well as the reaction kinematics for each measurement, are indicated in Table I.

TABLE I. The separation energy E_S, LAS laboratory scattering angle $\theta_{\rm LAS}$, GR detection energy $E_{\rm GR}$, and corresponding A_y data are displayed for each of the target nuclei. For the targets heavier than ^{4}He, integrated regions in E_S spectra for A_y calculations are listed in the E_S column. The setting angle of GR is always 25.5 degrees.

Target	E_S (MeV)	$\theta_{\rm LAS}$ (deg)	$T_{\rm GR}$ (MeV)	A_y
^{1}H	—	60.0	308.0	0.351 ± 0.007
^{2}H	2.2	59.4	305.0	0.349 ± 0.015
^{3}He	5.5	58.8	301.6	0.323 ± 0.018
^{4}He	19.8	55.5	286.1	0.236 ± 0.023
^{6}Li	19–32	54.5	281.5	0.213 ± 0.015
^{7}Li	23–32	54.5	280.3	0.176 ± 0.027
^{9}Be	20–40	54.0	279.2	0.171 ± 0.021
^{10}B	23–45	52.8	273.5	0.181 ± 0.021
^{11}B	32–51	51.5	267.7	0.125 ± 0.023
^{16}O	30–66	49.3	257.6	0.114 ± 0.060
^{19}F	32–68	49.3	257.6	0.043 ± 0.086

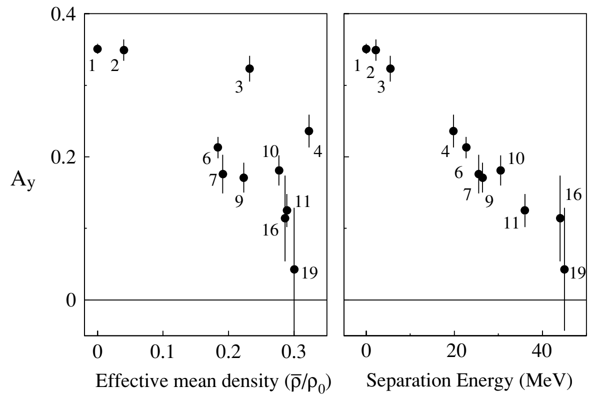

FIG. 2. Experimental analyzing powers for $(p, 2p)$ reactions from various nuclei plotted as a function of the ratio of the effective mean density, defined in Ref. [5], to the saturation density $\bar{\rho}/\rho_0$ (left panel) and also plotted as a function of the separation energy E_S (right panel). The numbers next to data points indicate target mass numbers. For the right plot, the values of separation energies for the targets heavier than ^{4}He were taken from Ref. [1]; these are consistent with the integrated regions of E_S listed in Table I.

In a previous paper, the A_y data were plotted as a function of the effective mean density [5] and it was shown that the suppression of A_y relative to the value for p-p scattering increases monotonically as the effective mean density increases. For comparative purposes, we display our data in a similar fashion in the left panel of Fig. 2. It is seen that our data follow a similar trend to that reported in Ref. [5] for most target nuclei but data for ^{3}He and ^{4}He nuclei significantly deviate from others. This plot suggests that the concept of effective mean density is not applicable for the lightest nuclei such as ^{3}He and ^{4}He, or alternatively it may suggest that the effective mean density is not the proper key parameter that characterizes the A_y suppression for these light targets.

The right panel in Fig. 2 displays the A_y data as a function of the separation energies E_S of the knocked-out protons. It is clearly seen that the data are much better correlated with E_S than with the effective mean density. This naively implies that the Q value of the reaction, namely the difference between the incident and final two-body energies, could be the key parameter that characterizes the suppression of A_y.

As already mentioned, it is known that relativistic effects cause a significant suppression of A_y for p-p scattering in the nuclear medium. We now examine the role of relativistic corrections for describing the A_y suppression for $1s_{1/2}$ proton knockout from the targets of interest. For this purpose, we compare the experimental data with several kinds of calculations, namely (a) the nonrelativistic plane-wave (NRPWIA) and distorted-wave (NRDWIA) model calculations, (b) NRDWIA calculations with relativistic corrections associated with the introduction of two different types of effective nucleon masses, and (c) full relativistic plane-wave (RPWIA) and distorted-wave (RDWIA) calculations based on the impulse approximation. In all of these calculations, the bound-state wave functions of the protons to be knocked out were based on the relativistic Hartree approximation using the computer code TIMORA [18]. The optical potentials were obtained in the relativistic impulse approximation using the code FOLDER, whereby scalar and vector densities, obtained with TIMORA, are folded with the Horowitz-Love-Franey representation of the NN amplitudes [18]. Even though this approximation may not be reliable for low-energy protons in the final channels, calculated A_y values for $(p, 2p)$ reactions are insensitive to the potential parameters [10,19]. For the nonrelativistic bound-state wave functions, we employed the upper component of the four-component relativistic bound-state wave function. For calculating the nonrelativistic scattering wave functions, we used Schrödinger equivalent optical potentials deduced from the relativistic scalar and vector optical potentials. The NRPWIA and NRDWIA predictions were based on the code THREEDEE [20], and some descriptions of the relativistic calculations are found in Refs. [10,21]. All of these calculations were performed with the zero-range approximation for the NN interaction.

In Fig. 3 we compare various model predictions with the analyzing power data. The thick solid line and the dashed line in the figure are the results of NRPWIA and NRDWIA predictions, respectively. The NRPWIA calculation is extended to $E_S = 0$, which corresponds to the p-p scattering value given by a phase shift analysis of free p-p scattering [22]. All DWIA calculations were performed for nuclei ranging from ^{4}He to ^{19}F. Because of shifts of the two-body kinematics caused by finite Q values of the reactions, these calculations display some dependence of A_y on E_S, but the experimental A_y values are much smaller than these theoretical predictions.

Since there is a good correlation between the A_y data and the separation energy, or equivalently the Q value of the reaction, one may speculate that the inclusion of the energy off-shell effect of the NN interaction could possibly explain the A_y

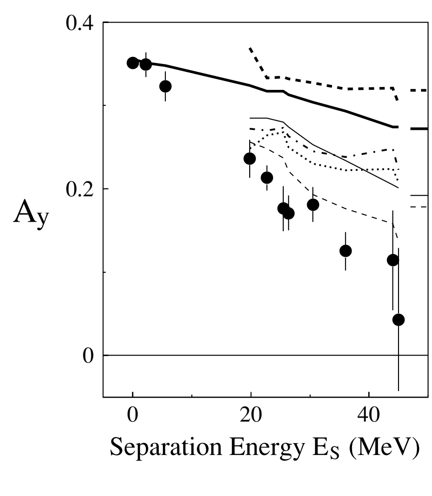

FIG. 3. Comparison of the experimental analyzing power A_y data to various model predictions plotted as functions of the separation energies. The thick solid (dashed) line represents a nonrelativistic PWIA (DWIA) prediction. The dotted line and the dotted-dashed line are Schödinger equivalent DWIA calculations made using radial-dependent and radial-independent effective-mass-type corrections to the NN interaction, respectively. The thin solid line and the dashed line indicate the results of full relativistic PWIA and DWIA predictions, respectively. The short horizontal lines in the right side correspond to calculations for a ^{40}Ca target (see the text).

suppression. In a trial calculation, however, the inclusion of the energy off-shell effect based on the AV18 *NN* potential [23] within the NRPWIA model caused a negligible change of less than 0.01 for A_y for the present kinematical conditions [24].

We now study the effect of medium modifications on A_y, since one expects the influence of density-dependent corrections to the *NN* interaction to be more significant for $1s_{1/2}$ knockout (than for knockout from other orbitals). Horowitz and Iqbal proposed a convenient way to handle relativistic corrections to the *NN* interaction by introducing the concept of a relativistic effective nucleon mass. We now consider the effect of such a correction to the NRDWIA. Essentially we follow a procedure similar to that outlined in Refs. [25,26] to calculate relativistic corrections to the nonrelativistic *NN* t matrix in the nuclear field. In particular, we consider two types of effective-mass-type corrections. The first approach is based on a local density approximation, where the radial-dependent effective nucleon mass $M_N^*(r)$ is given by

$$M_N^*(r) = [1 - 0.44\rho(r)/\rho_0]M_N$$

with M_N being the nucleon mass in free space, $\rho(r)$ the nucleon density as a function of the radius parameter r, ρ_0 the nuclear saturation density, 0.18 fm^{-3}, and 0.44 results from the Walecka model of mean-field theory [27]. The nucleon densities $\rho(r)$ are calculated within the context of the Dirac-Hartree approximation using the code TIMORA. The second type of correction is associated with a radial-independent effective nucleon mass M_N^* given by

$$M_N^* = (1 - 0.44\bar{\rho}/\rho_0)M_N,$$

where the procedure for calculating the effective mean nucleon density $\bar{\rho}$ is described in Ref. [5]. The actual NRDWIA calculations were performed using a density-dependent version of THREEDEE. The dotted line in Fig. 3, which represents the radial-dependent effective mass correction, explains about half of the observed A_y suppression. The effect of the radial-independent correction, represented by the dotted-dashed line, gives a trend similar to that of the more complicated local-density approximation. Both corrections underestimate the amount of suppression of the A_y data but seem to describe the trend of the data qualitatively, which illustrates the importance of including relativistic effective mass corrections to NRDWIA calculations for estimating the influence of the nuclear medium on the *NN* interaction. Note that the influence of this type of relativistic correction is reflected in terms of the deviation of the dotted and dashed-dotted lines from the thick dashed line. Therefore, in the case of ^{4}He target, the leftmost target for which DWIA lines exist, we see that the correction itself is remarkably larger than for other targets, but a totally similar suppression as in the case of other nuclei is given because of large distortion effects.

Finally, we show RPWIA and RDWIA calculations indicated by the thin solid and thin dashed lines, respectively. The distorted-wave predictions employ scattering wave functions that are solutions of the Dirac equation with complex scalar and vector optical potentials. The real parts of the scalar potentials are attractive and in essence also have the effect of reducing the nucleon mass as in a local density approximation. Hence, these calculations implicitly include the effective-mass-type corrections previously discussed. Within the context of the RDWIA, effective-mass-type corrections are viewed as a distortion effect to the bound-state and scattering wave functions.

In Fig. 3 it is seen that the RPWIA prediction gives a result that is similar to the NRDWIA predictions, which include effective-mass-type corrections. The RDWIA prediction is much closer to the data, though meaningful disagreement still exists. At this stage it would be too naive to trust these RDWIA calculations, since recoil corrections [28] have been ignored. For example, present RDWIA predictions yield cross-section peaks at positions of 30 MeV/c for ^{19}F and 100 MeV/c for ^{4}He in terms of the recoil momenta, whereas the experimental data and nonrelativistic calculations give peaks positions close to 0 MeV/c. Since it is known that A_y is sensitive to nonrelativistic spin-orbit distortions when the recoil momentum is not close to zero [4], the RDWIA calculation may overestimate the effect of distortion on A_y. We have estimated the effect of distortion in our relativistic model for a situation where the recoil effect is expected to be less serious, namely for $1s_{1/2}$ proton knockout from ^{40}Ca, for which the separation energy is 47 MeV. The results are indicated by short horizontal lines on the right side of Fig. 3. It is clear that the thick solid (NRPWIA), thick dashed (NRDWIA), and thin solid (RPWIA) lines are close to the corresponding lines for other targets, but this is not the case for the thin dashed line (RDWIA), which is close to the RPWIA prediction. This suggests that further theoretical effort on treatment of the recoil effect in the RDWIA, such as Ref. [28], is required to extract quantitative predictions for light nuclei.

In summary, we have presented new analyzing power data for $(p, 2p)$ reactions corresponding to $1s_{1/2}$ knockout from various nuclei ranging from ^{2}H to ^{19}F at an incident energy of 392 MeV. The data decrease monotonically as a function of the Q value for each reaction. It is also possible to consider that the A_y data decrease monotonically as a function of the effective mean density for most of targets, but significant deviations from this trend were observed for ^{3}He and ^{4}He target nuclei. The experimental data were compared to both non-relativistic and relativistic plane- and distorted-wave models. Nonrelativistic distorted-wave predictions are significantly improved by the inclusion of relativistic effective-mass-type corrections. In particular these corrections account for roughly half the observed suppression of the A_y data relative to the values for free p-p scattering. A relativistic plane-wave prediction, ignoring density-dependent corrections to the *NN* interaction, gives a result similar to the latter nonrelativistic prediction. A full relativistic distorted-wave model calculation predicts values that are closer to the data, though still significantly larger than the data. But further theoretical progress will be required to make quantitative claims about the apparent success of this model based on the relativistic Dirac equation, since recoil corrections, which are expected to be important for these light nuclei, have been ignored.

Our results imply that additional effects are required to explain experimental data. One such effect may be modification of the *NN* interaction themselves. As mentioned already, Krein *et al.* demonstrated that density-dependent corrections to meson-nucleon coupling constants and meson masses have the effect of suppressing the analyzing power and other spin observables [11]. To fully understand such an influence of the nuclear medium on the *NN* interaction, and to provide more stringent tests for the validity of relativistic and nonrelativistic models, it is highly desirable to measure data for various spin observables for this reaction.

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