TITLE: $\bar{p} + ^{13}\bar{C}$ ELASTIC SCATTERING AT 500 MeV

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ELASTIC SCATTERING AT 500 MeV

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ABSTRACT

For the first time, an elastic scattering experiment was performed at LAMPF using polarized protons and a polarized target nucleus ($p^{+13}C$). The analyzing powers $[A_{oon}(\Theta)]$ and $[A_{onn}(\Theta)]$ were measured using an incident beam energy of 500 MeV over the laboratory angular range of $10^\circ - 30^\circ$. Motivation for the experiment and some preliminary results and conclusions are presented.

INTRODUCTION

Since polarized protons became available, many experiments of $p$ - nucleus ($A$) elastic scattering involving spin observables were performed leading, in some cases, to exciting new results.$^{[1-6]}$ It is no surprise that the prospects of doing experiments with polarized nuclear targets has been further stimulated among the researchers in the field.$^{[7]}$ The new spin degree of freedom puts us on the frontier of new physics.

We point out here that after ten years of experimental and theoretical work, it is not certain that Schrodinger-equation-based models are adequate for describing $p + A$ interactions. The inability of such models to describe even qualitatively 500-MeV $p^{+40}Ca$ analyzing power $[A_p(0)]$ and spin-rotation $[Q(0)]$ data, and the fact that simple Dirac-optical model phenomenology fits these data exactly (see Fig. 1) generated much excitement in the medium energy physics community.$^{[3,4,8]}$ In this instance, the virtual pair process involving a beam proton and two target nucleons, a process automatically included in Dirac equation dynamics (Fig. 2) but not in the Schrodinger equation, accounts for most of the differences in the predictions for these spin observables.$^{[8]}$

We hope that other experiments might be able to provide data which could be used for continued studies of the relativistic versus nonrelativistic approaches. The standard Dirac equation impulse approximation model$^{[8]}$ (Dirac - IA) uses scalar, vector, pseudoscalar (or pseudovector), tensor, and axial vector forms for the Lorentz-invariant interaction, although this particular choice is not unique. The proton + spin-zero-target data are mainly influenced by the large scalar and time-like vector amplitudes. For the nonrelativistic (NR) model, it is the central and spin-orbit part of the effective nucleon-nucleon (NN) interaction that determine the $p + A$ (spin zero) elastic observables. Elastic data sensitive to the other pieces of the invariant interaction (or the NR effective interaction) would be interesting. Experiments with polarized targets ($A$) may provide such data.$^{[9,10]}$

Motivation for polarized proton + polarized target ($p + A$) experiments also stems from nuclear-structure considerations related to the fundamental difference between the nonrelativistic approach and the relativistic approach. The nonrelativistic models take conventional nuclear-structure input from mean-field theory or the shell model, while the relativistic approaches often utilize nuclear-structure information from relativistic mean-field theory. In the latter case, the wave functions have large upper and small
lower components. The large potentials in these models enhance the lower components, and polarized target elastic scattering experiments might provide direct confirmation of this enhancement (Fig. 3); such results would be of extreme interest to us.

A program of research using polarized nuclear targets (A) was recently initiated at the Los Alamos Clinton P. Anderson Meson Physics Facility (LAMPF). The first experiment, LAMPF E955: 500 MeV $\vec{p}^+ + ^{13}\text{C}$ Elastic Scattering, was proposed and performed to provide some data to help explore the topics mentioned above.

**EXPERIMENT**

The dynamic nuclear polarization (DNP) technique was used to polarize the $^{13}\text{C}$ nuclei.$[7,11]$ The target material was 99-atom-% $^{13}\text{C}$ enriched ethylene glycol, $^{13}\text{C}_2\text{H}_6\text{O}_2$, doped with the paramagnetic complex EHBA Cr(V) ($7 \times 10^{19}$ electron/cm$^3$). The material was in the form of beads about 1.5 mm in diameter filled into a 1-cm diameter
Fig. 2. The virtual pair process associated with a beam proton and two target nucleons is included in the Dirac equation dynamics but not those of the Schrodinger equation.

thin-walled (0.13 mm) teflon cell. The volume of the cylindrical target was 1.6 cm$^3$. The target was cooled using a $^3$He refrigerator (0.5K) with its axis parallel to the 2.5 T field of a C-type electromagnet (ZOLTAN). DNP occurs upon irradiating the target with microwaves of a frequency near 69 GHz. The effective thicknesses of $^{13}$C and $^1$H were 280 mg/cm$^2$ and 66 mg/cm$^2$, respectively. To keep the overall energy resolution near 1 MeV (FWHM), the mass surrounding the target was reduced to a minimum. One NMR coil was provided for both the $^{13}$C and $^1$H signals.
The target hydrogen polarization was also measured using a target polarimeter which monitored \( \vec{p} + \vec{p} \) elastic scattering at \( \Theta_{cm} = 46^\circ \) and relied upon the known values of \( A_y = A_{ooo} \) and \( A_{oonn} \) for 500 MeV \( \vec{p} + \vec{p} \). The \(^1\text{H}\) and \(^{13}\text{C}\) polarizations are related through the Equal Spin Temperature Theorem (EST).\(^{[11]}\)

\[
P = \tanh\left(\frac{\mu B}{k_B T_s}\right)
\]

where \( P \) is the proton \((^{13}\text{C})\) polarization, \( \mu \) is the proton \((^{13}\text{C})\) magnetic moment, \( T_s \) is the spin temperature (assumed equal for \(^1\text{H}\) and \(^{13}\text{C}\)), \( B \) is the field in which the dynamic cooling takes place, and \( k_B \) is the Boltzmann constant. The target polarimeter and the EST hypothesis proved indispensable during the experiment in that they allowed the effects of radiation damage to be directly determined and accounted for. Although the NMR and polarimeter results agreed exactly when the target material was fresh (i.e., not irradiated), the difference grew with increased beam flux through the target.\(^{[11]}\) These differences are expected because the polarimeter monitors the beam-target interaction region, while the NMR monitors a much larger volume. During the course of the experiment, the target material was annealed (7 times total) whenever target polarization dropped to one-half of its annealed value. Typical \(^{13}\text{C}\) polarization after annealing was 28%. A schematic of the target area showing the target polarimeter is shown in Fig. 4. Because of the beam deflection due to the polarizing magnetic field, care had to be taken to offset the incoming beam from the Line C optic-axis so that the incident protons passed through the center of the Zoltan electromagnet. The total beam deflection of Zoltan was 18°. Beam polarization (normal to the scattering plane and determined by \( \vec{p} + \vec{p} \) polarimeter located 10 m upstream of the target) was reversed in direction every 2 minutes. Target polarization (normal to the scattering plane) was reversed in direction approximately every 8 to 16 hours.

The High Resolution Proton Spectrometer (HRS) was used to analyze the momenta of the scattered 500-MeV protons and generated missing-mass spectra. Data were taken between c.m. angles 10° - 30° in about 1.5° - 2.0° steps for the \(^{13}\text{C}\) target and also for an empty target cell for background corrections. In addition, data were taken with this unpolarized \(^{13}\text{C}_2\text{H}_6\text{O}_2\) target, which was made by sandwiching ethylene glycol between two thin Be foils separated by 1 mm, to allow very accurate determination of the \(^{13}\text{C}/^{16}\text{O}\) cross section ratios. The data from the dummy target and the thin \(^{13}\text{C}\) target were crucial to the success of the experiment because the \(^{13}\text{C}\) and \(^{16}\text{O}\) elastic peaks were not well-resolved. Typical spectra are shown in Fig. 5.

A simplified discussion of the method used to extract the \( A_{ooo} \) and \( A_{oonn} \) from raw data follows. We have, introducing the notation \( \sigma \uparrow\uparrow \) (\( \sigma \) for beam up, target up), \( \sigma \uparrow\downarrow \) (\( \sigma \) for beam up, target down), etc.

\[
(\sigma \uparrow\uparrow + \sigma \downarrow\downarrow) - (\sigma \uparrow\downarrow + \sigma \downarrow\downarrow) = 4\sigma_{oC}P_t A_{ooo} \nonumber
\]

\[
(\sigma \uparrow\uparrow - \sigma \downarrow\uparrow) + (\sigma \downarrow\downarrow - \sigma \uparrow\downarrow) = 4\sigma_{oC}P_bP_t A_{oonn} \nonumber
\]

\[
(\sigma \uparrow\uparrow + \sigma \downarrow\uparrow) + (\sigma \downarrow\downarrow + \sigma \downarrow\downarrow) = 4\sigma_{oC} + 4\sigma_{oO} + 4\sigma_{oB} \nonumber
\]
Fig. 4. Schematic of target $\vec{p} + \vec{p}$ polarimeter.

Fig. 5. At $\Theta_{lab} = 27^\circ$, the missing-mass spectrum (500 Mev; $^1\text{H}$ + $^{13}\text{C}$ kinematics) for: (a) the $^{13}\text{C}$ ethylene glycol target, (b) the 1-mm thick unpolarized $^{13}\text{C}$ ethylene glycol target, and (c) the dummy (empty) flask.
Where it is assumed that "up" beam and target polarizations are the same as the "down" beam and target polarizations. The differences, of course, are accounted for properly in the actual data-reduction process. The first two equations generate the "difference missing-mass histograms," while the last equation generates the "summed missing-mass histograms." In the above equations cross sections \( \sigma \uparrow \), etc., refer to the observed experimental cross sections for all target material intercepted by the beam. On the right-hand sides of the equations, the quantities \( \sigma_{tC}, \sigma_{tO} \) and \( \sigma_{tB} \) are unpolarized cross sections due to \( ^{13}\text{C}, ^{16}\text{O} \), and background which contains everything else. \( A_{\text{ooon}} \) and \( A_{\text{oonn}} \) are non-zero for just the \( ^{13}\text{C} \) because only \( ^{13}\text{C} \) is polarized. Careful use of the difference and summed spectra allows very accurate extraction of \( A_{\text{ooon}} \) and \( A_{\text{oonn}} \). The dummy flask data and the thin ethylene glycol target enabled \( \sigma_{tC} \) to be accurately determined from the summed spectra without peak any peakfitting. Typical "difference" and "summed" spectra are shown in Fig. 6.

![Fig. 6. Typical “difference missing-mass” spectrum and “sum missing-mass” spectrum for \( \vec{p} + ^{13}\text{C} \) at \( \Theta_{\text{lab}} = 18^\circ \).](image)

RESULTS

The preliminary results of \( A_{\text{ooon}} \) and \( A_{\text{oonn}} \), deduced as described above, are shown in Fig. 7. The error bars result from a very conservative error analysis, which accounts for all sources of errors.

The interesting features of the data are: (1) \( A_{\text{ooon}} \) and \( A_{\text{oonn}} \) are not zero, but the values are small, generally less than 0.2; (2) structure is suggested in the region of the diffractive minima in the differential cross section as the case for \( A_y \) and \( D_{\text{toy}} \) [6] data; (3) \( A_{\text{ooon}} \) is always positive with maxima near 20° and 34°; (4) \( A_{\text{oonn}} \) has positive
Fig. 7. Experimental data and theoretical predictions for 497.5 MeV $p + ^{13}C$ target spin observables $A_{o0n}$ and $A_{00n}$. The RIA-DWBA predictions assuming RMF (nonrelativistic) value for the valence-neutron-lower component wave function are indicated by solid (dashed) curves. The NRIA—DWBA predictions are given by the dashed-dotted curves.

and negative values and bipolar structure with an apparent maximum near 20° and minimum near 25° and 34°.

Theoretical results for $A_{o0n}$ and $A_{00n}$ are shown in Fig. 1. These are RIA distorted-wave Born approximation (DWBA) model results and corresponding non-relativistic impulse approximation (NRIA)—DWBA model results. For both calculations the $^{13}C$ wave function was assumed to be a pure $1p_{1/2}$ neutron single-particle state coupled to an inert $^{12}C$ “core” and the scattering amplitude, corresponding to the twelve-nucleon core, was obtained from a Dirac phenomenological optical model fit to the 500-MeV $\vec{p} + ^{12}C$ elastic scattering data. Although there is good agreement between the band, defined by RIA—(DWBA) and NRIA—(DWBA), and the $A_{o0n}$ data, the data are clearly not able to select a particular line from within this band. However, it is interesting that both curves reproduce the qualitative features of the data. The agreement for the case of $A_{00n}$ is not as good; it is interesting here that the $A_{00n}$ data oscillate about zero and so do the calculations, although the experimental and theoretical oscillations appear to be out of phase. Unfortunately, there are no results from a rigorous nonrelativistic model with which to compare these new results. For $A_{o0n}$ the dotted curve shown in Fig. 7 is the result of a nonrelativistic calculation based on the Glauber model. This calculation fails to qualitatively describe the data.

In summary, there are a variety of experimental and theoretical motivations for polarized proton + polarized-target elastic experiments. The results from LAMPF E955, $\vec{p} + ^{13}C$ Elastic Scattering at 500 MeV, have shown that such experiments are difficult, but that they can be done. The preliminary data suggest that the relativistic model may be adequate, but a sophisticated nonrelativistic model must be developed.
before more comparison and detailed statements can be made. Also, more and better-quality data are needed if the small subtle differences within a given model are to be studied, for example, lower-component enhancement.

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REFERENCES


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