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ANALYZING POWER OF CARBON FOR INCIDENT PROTONS BETWEEN 440 AND 640 MeV

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Nucl. Instr. and Methods

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ABSTRACT

The effective analyzing power of carbon for polarized protons in the energy range 440 to 640 MeV was measured as a function of proton scattering angle. The measurements were made by observing the azimuthal scattering asymmetry produced by a 650-MeV, 75% polarized beam of protons in a large carbon-plate spark chamber. No attempt was made to separate out the contribution of inelastic channels which resemble proton-carbon scattering. An enhancement of p-C analyzing power in the neighborhood of 650 MeV is observed and a possible explanation of this effect is discussed.

I. INTRODUCTION

The study of polarization effects of nucleons scattered from various nuclei has been an important tool in understanding the complexity of nuclear forces. Of the many target nuclei available carbon has been the most widely studied.[1-11] From the existing proton-carbon data a general theoretical understanding of the gross features of polarization in scattering has been achieved over a limited range of energies (100 to 300 MeV). The scattering asymmetry property of polarized nucleons is also extensively used in the measurement of the polarization of fermions produced in other interactions (e.g. pion-nucleon experiments designed to measure the polarization of the recoil nucleon). Again carbon is frequently chosen as the analyzing scatterer because it yields measurable asymmetries, is easy to work with, and a large amount of calibration data exists.

However, above 400 MeV data is sparse and optical model predictions tend to disagree with the data, most likely because of increasing limitations in angular and energy resolution at the higher energies. The effect of inelastic scattering is important at the larger angles and higher proton energies. Hence the motivation for this present experiment has been to deduce the effective analyzing power of carbon used in experiments studying the polarization of fermions and to survey proton-nucleus polarization effects as a function of energy in the 400 to 700 MeV range.

II. EXPERIMENTAL METHOD

The measurement of the analyzing power of an element for polarized nucleons requires that one find an azimuthal scattering asymmetry produced by a beam of protons of given polarization. The magnitude of the analyzing power, A, is determined from the angular distribution of the polarized

protons scattered by the analyzer according to the expression[12]

$$\sigma(\theta,\emptyset,T) = \sigma_o(\theta,T)\ [1 + PA(\theta,T)\cos\emptyset] \qquad (1)$$

where P is the polarization of the incident beam, $A(\theta,T)$ is the analyzing power of the element for collisions in which protons of energy T are deflected through an angle θ, $\emptyset$ is the azimuthal angle between the plane of scattering and the plane normal to the direction of polarization of the incident proton beam.

In this experiment, two large carbon-plate spark chambers were used in tandem as analyzer-detectors. The front chamber consisted of three thin plates followed by 32 one-inch thick graphite plates; the second chamber consisted of 25 one-inch graphite plates followed by 5 one-half inch and 5 quarter-inch plates. The one inch thickness of the graphite plates permitted precise definition of incident proton energy. The chambers' combined large volume allowed the simultaneous measurement of the effective carbon analyzing power over a wide energy and angular range.

The polarized proton beam was provided for us by a double scattering experiment conducted in front of our spark chamber set-up.[10] The polarization and energy of the beam was 75% and 650 MeV respectively A 680 MeV, 55% polarized beam was also used for part of the running to gather more data at the higher energies and to provide an internal consistency check on the measured asymmetries.

III. DATA ANALYSIS

The calculation of the analyzing power of carbon was performed in two steps. First the spark chamber film was scanned and a total of 40 000 scatters was found and measured. Each selected scatter was geometrically and kinematically reconstructed. For each of the two orthogonal views the

proton carbon scattering angle and sense, and the number of carbon plates traversed by the proton before scattering were recorded. No attempt was made to estimate the elasticity of scattering by range because of the complex behavior of most protons before stopping. (Only ~ 2% of the protons traversed their appropriate range without interacting; and only ~ 10% of the protons reached the back chamber without scattering.) An event was accepted if the first distinct scatter in the plane normal to the beam polarization exceeded 5 deg. The residual trajectory following each first scattering was ignored; only single prong events were accepted. Thus we include the contribution of all inelastic channels which may resemble elastic proton-carbon scattering (see Sec. IV.).

Secondly, the analyzing power was then estimated by grouping events into given incident energy and angular intervals and applying the maximum-likelihood method to these bins. The energy-angle bin size was chosen to be compatible both with the resolution of the experimental system and with a reasonable statistical uncertainty for the analyzing power to be derived from any one bin. Since the incident polarized proton beam possessed an energy spread of ± 10 MeV, and the energy resolution due to the one inch thickness of the carbon plates was 10 MeV, we selected ± 20 MeV for the energy interval. The angular bin size was ± 1.5 deg, roughly matching the angular measurement resolution of ± 1 deg. In order to obtain a better profile of the energy and angular behavior of the analyzing power, we overlapped the bins so that the analyzing power was calculated at 20 MeV and 1.5 deg energy and angular intervals. Thus adjoining data points are not statistically independent.

The maximum likelihood theorem[13] applied to Eq. (1) states that for a known beam polarization P, A is that value which allows the observed

array of events in the sample to be consistent with the maximum probability of observing that sample. The expression

$$L(A) = \prod_{i}^{\text{events}} [1 + AP \cos \phi_i]$$

is thereby maximized.

In our case about 80% of the events were collected with P = 0.75; the remaining events were collected with P = 0.55. The statistical error ΔA is arbitrarily defined as that increment of A which makes L/L_{max} equal to $e^{-1/2}$.

Scanning for valid events was conducted in a random fashion. Scanning bias effects are believed to be small. To confirm this all film was scanned twice, the second scan being performed with the film reversed so that the right-hand appeared left to the scanners and vice versa. The average scanning efficiency was 75%. The analyzing power estimated from this rescan agreed within statistics with that obtained from the first scan. Distortion in the spark chamber optical system was visually detectable; a first order correction for this distortion was made by measuring the local deviation from a known orthogonal grid projected by the optical system and applying this correction factor to each event. The difference in the analyzing power before and after the distortion correction was applied varied from 0 to 0.03. No significant asymmetry in the plane of the beam polarization was found. The uncertainty in the analyzing power resulting from the uncertainty in the beam polarization can be obtained by investigating the changes in the calculated analyzing power when the beam polarization is modified within the limits of error. The beam polarization is believed known to ± 0.03; the propagated deviation in the analyzing power was ± 0.03.

The resulting analyzing power of carbon as a function of proton energy and scattering angle are given in Table I.

IV. DISCUSSION OF RESULTS

In Fig. 1 the analyzing power for five selected angles is plotted as a function of energy along with the results of three other experiments performed at energies near our energy range. At the smaller angles where the inelastic channels play a small role, our spark chamber data join remarkably well with the experimental values of Heiberg[7] at 424 MeV and Azhgirey[9] at 660 MeV. Starting at 424 MeV the analyzing power slowly and monotonically decreases as the proton energy increases. But at 600 MeV the analyzing power begins to rise again, peaking near 650 MeV. The data of Azhgirey at 660 MeV and McManigal[10] at 730 MeV adds further credibility to the existence of an enhancement in the analyzing power near 650 MeV. Accompanying this behavior of the analyzing power is a rapid increase in the p-C differential cross section at forward angles. As shown in Fig. 2, the p-C differential cross section at 6 deg increases two-fold between 400 and 700 MeV.

A possible explanation of this phenomenon is that it reflects the known behavior of the nucleon-nucleon cross section between 400 and 800 MeV. The proton-proton cross section doubles in this energy range.[14] This sharp rise in the total cross section is attributed to meson production. It has been noticed that the center of the rise occurs approximately at 630 MeV.[14,15] At this energy the total kinetic energy available in c.m. is 290 MeV which equals the sum of a pion mass and the Q-value for the 3-3 resonance. (Note that in the case of a proton being scattered by a nucleon that is bound in a nucleus, the energy must be augmented by the average nuclear potential

well depth, making the threshold for this process about 650 MeV.) The possibility that the nucleon-nucleon elastic scattering amplitude may be substantially enhanced due to the opening of a strong inelastic channel has been investigated by Leung.[16] The elastic and inelastic channels are coupled through the unitarity condition and he shows that a maximum results in the elastic scattering amplitude. The sharp rise in the elastic cross section, for forward angles, above 400 MeV should be expected because of the increasing diffraction scattering accompanying the increasing inelastic cross section.

Thus it seems plausible that the behavior we find in the analyzing power may be a reflection of the enhanced elastic scattering amplitude, according to the arguments above, assuming these arguments to be applicable to nucleons in nuclei. A more thorough survey of this energy region is needed before more positive conclusions may be made.

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FOOTNOTES AND REFERENCES

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FIGURE CAPTIONS

Fig. 1. The effective analyzing power of carbon as a function of incident proton kinetic energy. □ - Ref. 7, ○ - Ref. 9, ■ - Ref. 10, and ● - this experiment. This experiment includes the contribution of all inelastic channels which may resemble proton-carbon scattering.

Fig. 2. Proton-carbon differential cross section at 6 deg (proton scattering angle in lab), as a function of proton kinetic energy. ● - Ref. 6, ■ - Ref. 7, △ - Ref. 9, ○ - Ref. 10, □ - Ref. 11.

Table I. The effective analyzing power of carbon as a function of proton scattering in the lab and incident proton kinetic energy. The values quoted include the contribution of all inelastic channels which may resemble proton-carbon scattering.

	Incident Proton Energy (MeV)										
θ_{Lab} (deg)	440	460	480	500	520	540	560	580	600	620	640
5.6	0.15±.16	0.32±.14	0.24±.12	0.18±.10	0.25±.09	0.20±.08	0.19±.08	0.19±.06	0.20±.06	0.30±.06	0.36±.07
6.2	0.22±.12	0.37±.10	0.33±.08	0.22±.08	0.26±.06	0.20±.08	0.18±.06	0.18±.06	0.25±.06	0.35±.05	0.42±.06
7.5	0.36±.10	0.37±.09	0.42±.08	0.34±.07	0.26±.06	0.24±.06	0.20±.06	0.20±.06	0.31±.05	0.40±.05	0.44±.05
9.0	0.37±.09	0.32±.09	0.36±.08	0.38±.08	0.25±.06	0.26±.06	0.26±.05	0.23±.06	0.32±.05	0.40±.05	0.46±.06
10.5	0.27±.10	0.24±.09	0.31±.08	0.31±.07	0.23±.07	0.25±.06	0.38±.06	0.26±.06	0.30±.05	0.35±.05	0.41±.06
12.0	0.31±.10	0.26±.09	0.27±.08	0.30±.08	0.28±.08	0.25±.07	0.21±.07	0.18±.06	0.26±.06	0.32±.06	0.38±.07
13.5	0.34±.10	0.35±.10	0.34±.09	0.35±.09	0.35±.08	0.33±.07	0.29±.07	0.22±.07	0.30±.06	0.38±.06	0.40±.07
15.0	0.39±.12	0.44±.10	0.35±.10	0.35±.09	0.35±.08	0.40±.07	0.30±.07	0.24±.07	0.27±.06	0.34±.06	0.35±.07
16.5	0.39±.12	0.39±.10	0.23±.10	0.17±.10	0.23±.09	0.31±.08	0.28±.07	0.24±.07	0.24±.06	0.30±.06	0.33±.07
18.0	0.20±.12	0.25±.12	0.26±.10	0.17±.10	0.17±.09	0.30±.09	0.20±.08	0.20±.07	0.20±.07	0.27±.06	0.36±.08
21.0	0.24±.10	0.33±.11	0.36±.10	0.23±.10	0.27±.09	0.27±.09	0.16±.08	0.12±.07	0.18±.07	0.33±.07	0.32±.09
24.0	-0.03±.10	-0.05±.12	0.22±.11	0.29±.10	0.20±.10	0.26±.09	0.12±.09	0.15±.08	0.26±.08	0.22±.08	0.33±.09

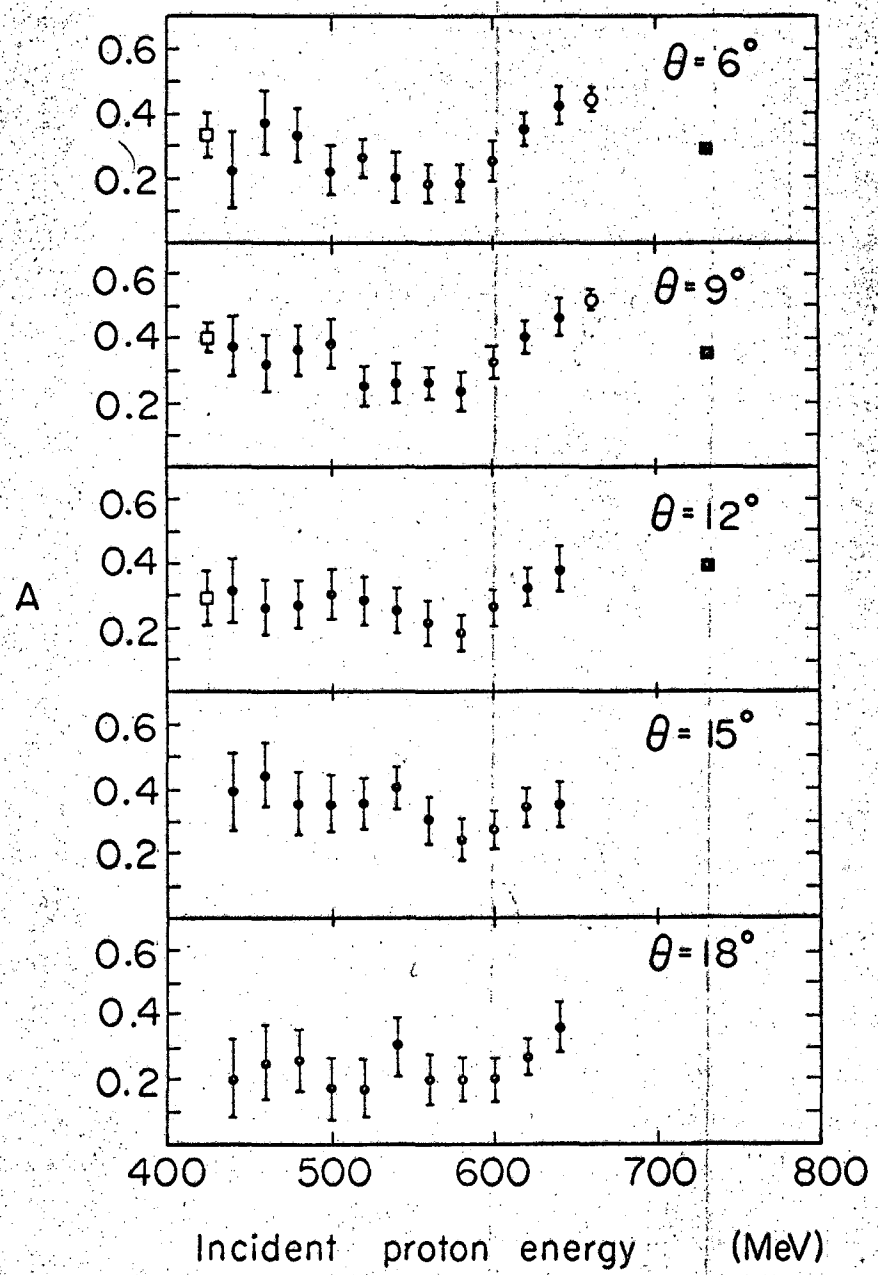

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FIGURE 1

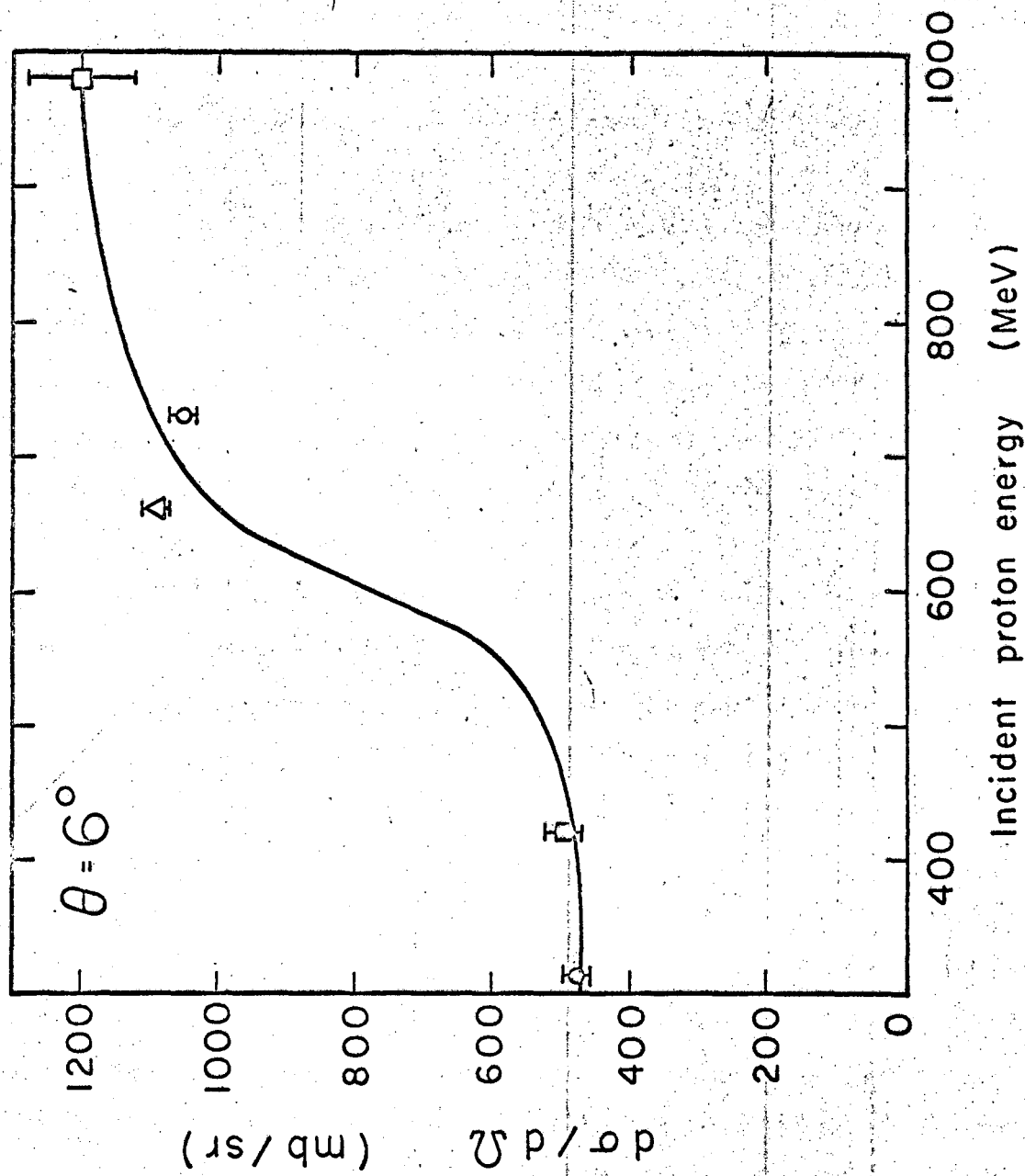
θ = 6°
dσ/dΩ (mb/sr)
1200
1000
800
600
400
200
0
400
600
800
1000
Incident proton energy (MeV)
MUB-3170

FIGURE 2

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