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Analyzing Power in Large-Angle Proton-Neutron Elastic Scattering

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The large-angle analyzing power A in proton-neutron elastic scattering at 2, 3, and 6 GeV/c with use of the polarized proton beam at the Argonne zero-gradient synchrotron and a liquid deuterium target have been measured. The measurements, the first at high energy, show that A is large (20–40%) and negative over much of the angular range and shows no decrease with incident energy, unlike the earlier data at smaller angles.

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The analyzing power A for p-p elastic scattering has been well-measured over the full available angular range with increasing accuracy over the past two decades. Measurements made at the Argonne zero-gradient synchrotron (ZGS) in the past few years are particularly accurate from 2 to 12 GeV,[1] enabling a good determination of the energy and angular dependence of the $I=1$ spin-flip amplitude from the phase-shift region up to high energies. The only existing high-energy neutron-proton analyzing-power data[2,3] have been confined to near forward to backward scattering. However, these data have shown that the energy and angular dependence of the small-angle n-p analyzing power is very different from that of proton-proton scattering; in particular the $I=0$ single-flip amplitude has an anomalously rapid energy dependence. The existence of a new low-lying $I=0$ Regge trajectory (ϵ) has been postulated in an attempt to understand this behavior.[4]

On the other hand, the data for n-p charge exchange have shown a large energy-independent analyzing power for $u \sim 1$ (GeV/c)^2, similar except for sign to that in $pp \to \Delta^{++}n$.[5] It has been suggested[6] that there may be a strongly spin-dependent constituent-scattering amplitude which interferes with the pion exchange to produce these large spin asymmetries. Thus the need for an investigation of the n-p spin-flip amplitude at large angles seems compelling, especially since measurements of large-angle p-p spin observables have recently been interpreted in terms of scattering of constituents.[7]

The experiment was performed at the Argonne ZGS with a polarized proton beam incident on a 30-cm liquid deuterium target. The beam polarization was monitored before injection into the ZGS and immediately after extraction from the accelerator. A portion of the extracted beam was then transported to the area used for this experiment. The beam polarization was typically 70%, in the vertical direction, at all momenta. The spin direction was reversed on every accelerator pulse.

The incident beam was defined by two small scintillation counters (2.5 cm diam) and its position measured by a scintillation-counter hodoscope with a resolution of ±2.5 mm. Since the illumination source was the extraction point from the ZGS (approximately 100 m upstream) the actual spot was small, 6 mm full width at half maximum, and had a small divergence, <1 mr. The target was a closed-cycle self-refrigerating cylinder, 30 cm long and 8 cm in diameter, filled with liquid deuterium. The target was emptied for background measurements periodically throughout data collection.

The experimental apparatus, shown in Fig. 1, consisted of a large solid-angle nonmagnetic double-arm spectrometer. Each of the two movable arms contained two trigger counters (S) before and after a set of three double (x-y) proportional wire planes (PC). Most of the remaining solid angle, as viewed from the target, was covered by an array of veto counters (V) consisting of lead-scintillator sandwiches. The right arm of the spectrometer (the neutron arm) also contained a charged-particle counter (C) and 3 to 6 cm of brass (B), the thickness of which varied according to the scattered neutron energy. The

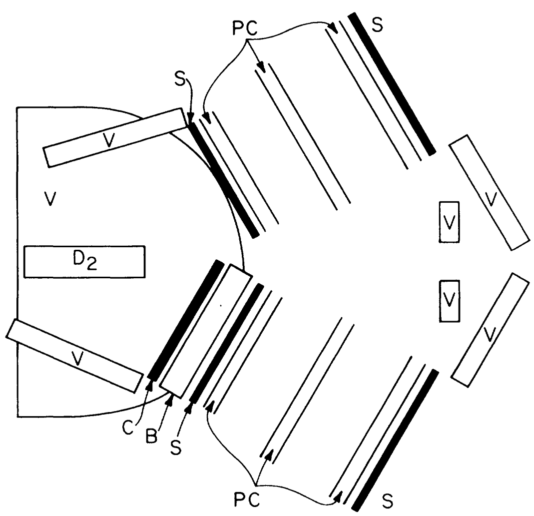

FIG. 1. A plan view of the spectrometer. The semicircular veto counters were placed above and below the deuterium target. See text for other details.

brass served as a secondary target for neutron interactions. Those interactions which produced energetic charged particles were detected in the proportional-chamber system downstream of the brass. The trigger required a beam particle coincident with the four trigger counters, and the absence of a signal from the veto counters.

The geometric reconstruction of an event then consisted of (a) finding a track in the left arm (the proton arm), (b) extrapolating to the target region and determining the interaction vertex by intersecting the track with the beam track, (c) finding one or more tracks downstream of the brass, (d) extrapolating a single track to the center of the brass, or multiple tracks to their common vertex in the brass, and (e) with use of the vertex position and the coordinates in the brass to determine the angles of the particle in the right arm. Events with multiple tracks in the left arm or multiple interaction vertices in the brass were discarded.

The events were characterized as proton-proton or proton-neutron scatters by the presence or absence of a signal in the scintillation counter placed immediately upstream of the brass converter. Since a large fraction of the neutron-type triggers were generated by the conversion in the brass of photons from π^0 decay, a 1-cm sheet of lead (1.4 radiation lengths) was placed in front of this counter. This reduced the inelastic contamination of the neutron events at the expense of the proton-proton signal. Since the neutron conversion process has an inherently low efficiency (ranging from 2% to 10%, depending on kinematics), this shift of the contamination into the relatively clean proton channel is desirable.

The kinematic reconstruction of the events is based on our measurements of the angle and momentum of the incident proton and of the scattering angles of the two particles in the final state. Variables related to the coplanarity (the triple scalar product of the unit vectors for the incident and final particles) and $\Delta\theta$ (the difference between the angles measured for a final particle and predicted from the other) were defined for each event. Although both resulting distributions were broadened by Fermi motion, a clear elastic signal could be isolated in all kinematic regions.

As a check on the separation of proton and neutron events, the angle between the particle incident on the brass converter and the smallest-angle particle to emerge from the brass was examined. For proton scattering events, tagged by the scintillator before the brass, this distribution was very sharply peaked at small angles (less than 6°), corresponding to no interaction apart from multiple Coulomb scattering in the brass. For neutron-target data, the distribution was much broader, with substantial data in the region above 30°. This distribution was closely monitored; if an identifiable small-angle peak in the neutron data was observed, only events with this conversion angle well outside the corresponding proton-data peak were used. The remaining data were then corrected for the small residual contamination. This correction was only necessary at large $|t|$, and corresponded to, at most, 5% of the data.

The above analysis procedure was performed independently for data collected with the beam polarized up and down. If the number of elastic events in a particular $|t|$ range with beam spin up (down) is denoted $N_\uparrow$ ($N_\downarrow$), then the analyzing power is defined as

$$A = P_B^{-1}(N_\uparrow - N_\downarrow)/(N_\uparrow + N_\downarrow).$$

The beam polarization, P_B, was corrected to account for the average difference between the scattering plane and horizontal plane, typically a 3% effect. The variable t is defined as the square of the momentum transfer from the beam to the particle in the left (proton) arm. Forward- and backward-angle data are combined for proton-proton events (the forward and backward data sets were consistent at all momenta).

The data for the p-n analyzing powers are shown in Fig. 2. The errors include the statistical errors associated with the background subtraction procedure but do not include a possible ±5% uncertainty in the absolute calibration of the beam polarization monitors. This uncertainty is multiplicative and therefore small when the analyzing power is small. The relative determination of the beam polarization within a single incident momentum is determined to better than ±1%. The data cover the moderate to large-$|t|$ region; the minimum accessible laboratory angle was 10°–12°. The proton-proton data are plotted in Fig. 3 along with some previous large-angle data[1]; our 2- and 3-GeV/c data agree with those of Albrow *et al.*[1] The data are systematically higher than those of Parry *et al.*,[1] and Neal *et al.*,[1] and lower than those of Miller *et al.*,[1] and represent an improvement in precision over all of these data. At 6 GeV/c there is good agreement with Fernow *et al.*,[1] but our points are lower than the later, more precise data of Krisch[1] near 90° c. m. For the neutron-proton data, the agreement with the smaller-angle measurements of Diebold *et al.*[2] is good in the regions where there is overlap (at the lower energies) and joins smoothly onto that of Abolins *et al.*[3] in the backward direction.

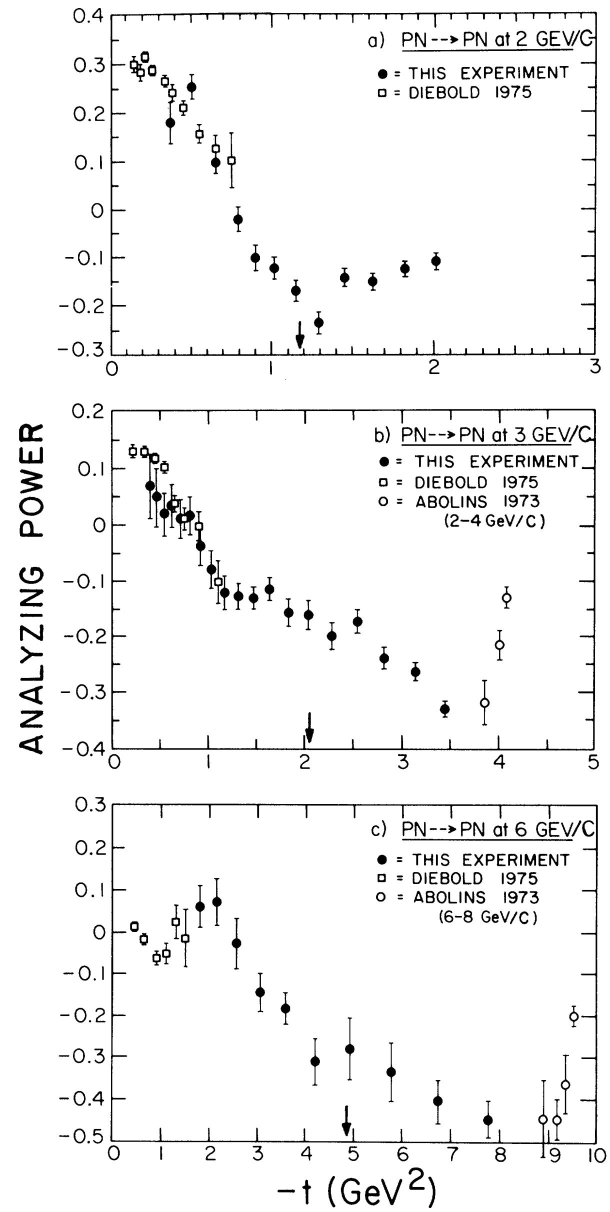

FIG. 2. The analyzing power for elastic proton-neutron scattering at incident momenta of (a) 2 GeV/c, (b) 3 GeV/c, and (c) 6 GeV/c. Some of the existing small-angle data (Ref. 2) and very large-angle data (Ref. 3) are also shown. The 90° c.m. points are indicated by arrows.

The general feature of the data is that the large-angle n-p analyzing power is larger in magnitude

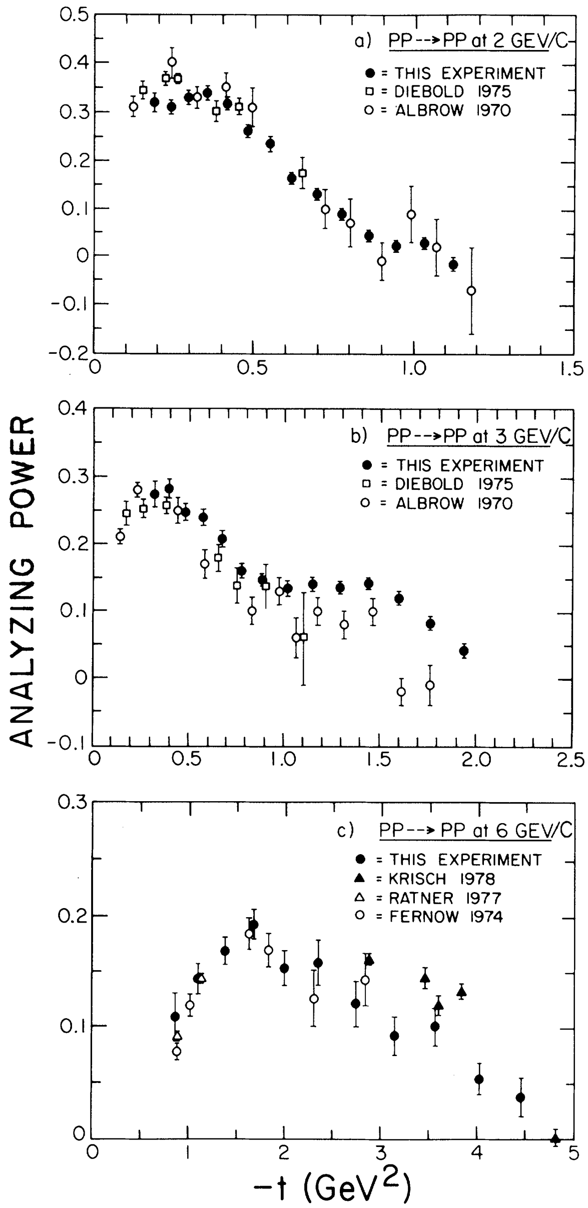

FIG. 3. The analyzing power for elastic proton-proton scattering at incident momenta of (a) 2 GeV/c, (b) 3 GeV/c, and (c) 6 GeV/c. Some of the existing data in the large-angle region are also shown (Ref. 1).

and of the opposite sign to that for p-p scattering. At 90° c. m., where the p-p analyzing power is constrained to zero because of particle identity, the n-p analyzing power is increasing with energy, and reaches a value of −0.35 at 6 GeV/c. Regge exchange models are not expected to give reliable predictions at these large values of momentum transfer.

The quark-interchange-model calculations that have been done[7] have focused on providing an understanding of the rapid energy dependence and the large magnitude of the spin-correlation parameter, A_{nn}, measured at the Argonne ZGS.[8] The assumption of helicity conservation in the quark-quark subprocess is basic to these calculations, and this assumption implies that the analyzing power should vanish at all angles. The neutron-proton system provides the appropriate test of this assumption since there is no constraint that the analyzing power vanish at 90°, which is where quark-interchange models and QCD (quantum chromodynamics) are most reliable. Thus the fact that the large-angle n-p analyzing power is large, and an increasing function of incident momentum, at least up to 6 GeV/c, is not consistent with a simple constituent picture of the interaction.

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[1]R. D. Klem *et al.*, Phys. Rev. D 15, 602 (1977); D. Miller *et al.*, Phys. Rev. D 16, 2016 (1977); R. C. Fernow *et al.*, Phys. Lett. 52B, 243 (1974); M. Borghini *et al.*, Phys. Rev. D 17, 24 (1978); A. D. Krisch, Brookhaven National Laboratory Report No. BNL-50947, 1978 (unpublished), p. 346; R. E. Diebold *et al.*, Phys. Rev. Lett. 35, 632 (1975); earlier data, M. G. Albrow *et al.*, Nucl. Phys. B23, 445 (1970); J. H. Parry *et al.*, Phys. Rev. D 8, 45 (1973); Homer A. Neal and Michael J. Longo, Phys. Rev. 161, 1374 (1967).

[2]R. E. Diebold *et al.*, Phys. Rev. Lett. 35, 632 (1975); see also D.G. Crabb *et al.*, Phys. Rev. Lett. 43, 983 (1979).

[3]M. A. Abolins *et al.*, Phys. Rev. Lett. 30, 1183 (1973); see also P. R. Robrish *et al.*, Phys. Lett. 31B, 617 (1970).

[4]E. L. Berger *et al.*, Phys. Rev. D 17, 2971 (1978).

[5]A. B. Wicklund, ANL Report No. ANL/HEP 75-02 (unpublished), Section III; R. E. Diebold, in *High Energy Physics with Polarized Beams and Targets—1976*, edited by M. L. Marshak, AIP Conference Proceedings

No. 35 (American Institute of Physics, New York, 1977), p. 92.
[6]F. E. Low, in *Higher Energy Polarized Beams—1977*, edited by A. D. Krisch and A. J. Salthouse, AIP Conference Proceedings No. 42 (American Institute of Physics, New York, 1978), p. 35.
[7]G. R. Farrar *et al.*, Phys. Rev. D 20, 202 (1979); S. J. Brodsky *et al.*, Phys. Rev. D 20, 2278 (1979).
[8]J. R. O'Fallon *et al.*, Phys. Rev. Lett. 39, 733 (1977); D. G. Crabb *et al.*, Phys. Rev. Lett. 41, 1257 (1978).

Inclusive Muon Production at c.m. Energies 12 to 31.6 GeV

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In this Letter, a measurement of inclusive muon production ($p_\mu > 2$ GeV/c) in e^+e^- annihilation into hadrons at center-of-mass energies from $\sqrt{s} = 12$ to 31.6 GeV is reported. The results agree with the expected semileptonic decays from charmed and bottom mesons.

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Many features of e^+e^- annihilation into hadrons are successfully described by assuming the production of u, d, s, c, and b quarks which then fragment into hadrons.[1] One of the central points in elementary particle physics today is the success of gauge theories in incorporating these quarks into a common framework with the more directly observable leptons. Just as the weak de-

