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NEUTRON-PROTON ELASTIC SCATTERING FROM 1 TO 6 GeV*

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In this Letter we are reporting the first high-energy measurements (1- to 6.3-GeV kinetic energy) of neutron-proton elastic scattering extending from the small-angle, diffraction-peak region to the region beyond 90° in the center-of-mass system. Previous high-energy measurements[1,2] have concerned only elastic neutron-proton scattering near 180° in the so-called charge-exchange backward-peak region. This experiment was carried out at the Bevatron of the Lawrence Radiation Laboratory and used a neutron beam, spark chambers, and a liquid-hydrogen target. There were three objectives in this experiment: (1) to verify the existence of the expected but hitherto unobserved diffraction peak, to determine its parameters, and to investigate possible shrinkage; (2) to examine the differential cross section at and beyond 90° in the center-of-mass system, a region inaccessible in proton-proton scattering; (3) to look for the secondary forward peak which appears in pion-proton elastic scattering[3,4] but not in proton-proton elastic scattering.

The experiment involved a new technique using a neutron beam containing neutrons of all energies up to 6.3-GeV kinetic energy. Neutrons, produced by the external proton beam of the Bevatron hitting a beryllium target, were formed into a beam by a 15-foot-long lead collimator set at 1° to the proton-beam direction. Bending magnets removed charged particles from the beam and lead plates reduced gamma-ray contamination. From analysis of the elastic events, the neutron spectrum was found to peak at 5.0 GeV and two-thirds of the neutrons which gave events had energies above 4.0 GeV. Thus, this is a high-energy beam and, in fact, the spectrum was more favorable than expected.

The neutron beam with a diameter of 1.25 inches interacted in a 12-inch-long hydrogen target as shown in Fig. 1. A system of thin-plate spark chambers and a magnet were used to detect the recoil proton from the elastic scattering and to measure its angle and momentum. A set of seven spark chambers with $\frac{3}{16}$-inch-thick stainless-steel plates was used to detect the scattered neutron by its interactions. The interaction or conversion of the neutron appeared as a neutron star of one or more prongs. The proton-detecting system and the neutron-detecting chambers were both on a circular rail centered on the hydrogen target. With seven different settings of their positions, all scattering angles at all energies above 1 GeV were covered. The spark chambers were triggered when a set of long, horizontal, scintillation counters interspaced among the neutron chambers and two long, horizontal, scintillation counters, P_1 and P_2, in the proton system indicated that an approximately coplanar event had occurred.

The angle of the incident neutron was known to ±0.2 deg and the angle of the scattered neutron, determined by the line from the interaction point in the target to the conversion point in the neutron spark chambers, was known to ±0.5 deg. These angles, combined with the angle and momentum of the recoil proton, overdetermined an elastic scattering, and yielded the incident neutron energy. The energy dependence of the conversion efficiency of the neutron spark chambers was measured by setting up the apparatus for small-angle scattering and triggering only with the proton-system counters. At small angles the recoil proton angle and momentum was sufficient by itself to determine an elastic scattering. The fraction of events which showed neutron conversion in the neutron chambers then gave directly the conversion efficiency. This efficiency was 62% at 6 GeV and dropped to 45% at 2 GeV.

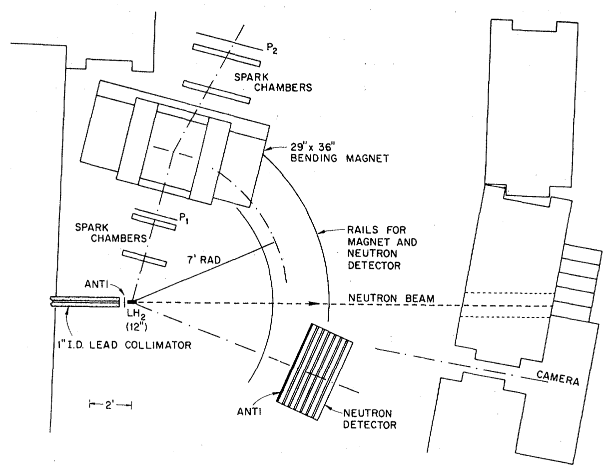

FIG. 1. Layout of experimental apparatus.

Corrections have been applied to the data for angular bias in the spark chambers, multiple scattering in the hydrogen target, small-angle cutoffs, and inelastic contamination. The relative normalization between the different settings was obtained by two sets of scintillation counters which measured the scattered charged-particle flux from the hydrogen target. No absolute normalization was available from the experiment itself. We have normalized the data by fitting the small-angle regions with an exponential in t, the square of the four-momentum transfer from the incident to the scattered neutron, and by using the optical theorem and the neutron-proton total cross sections.[5] We took the real part of the forward-scattering amplitude to be zero.[6]

For presentation we have grouped the events into ranges of incident-neutron kinetic energy. The data presented are based on 6219 elastic events which represent about 15% of our available data. Figure 2 is a semilogarithmic plot of the differential cross sections $d\sigma/d|t|$ vs $|t|$ [$|t|$ is expressed in $(\text{GeV}/c)^2$].

In terms of the center-of-mass scattering angle θ^* and the center-of-mass momentum p^*,

$$|t| = 2p^{*2}(1-\cos\theta^*)$$

and

$$d\sigma/d|t| = (\pi/p^{*2})d\sigma/d\Omega^*.$$

The cross sections as a function of $\cos\theta^*$ may be computed from $d\sigma/d|t|$ using the average values of p^* for each incident energy range

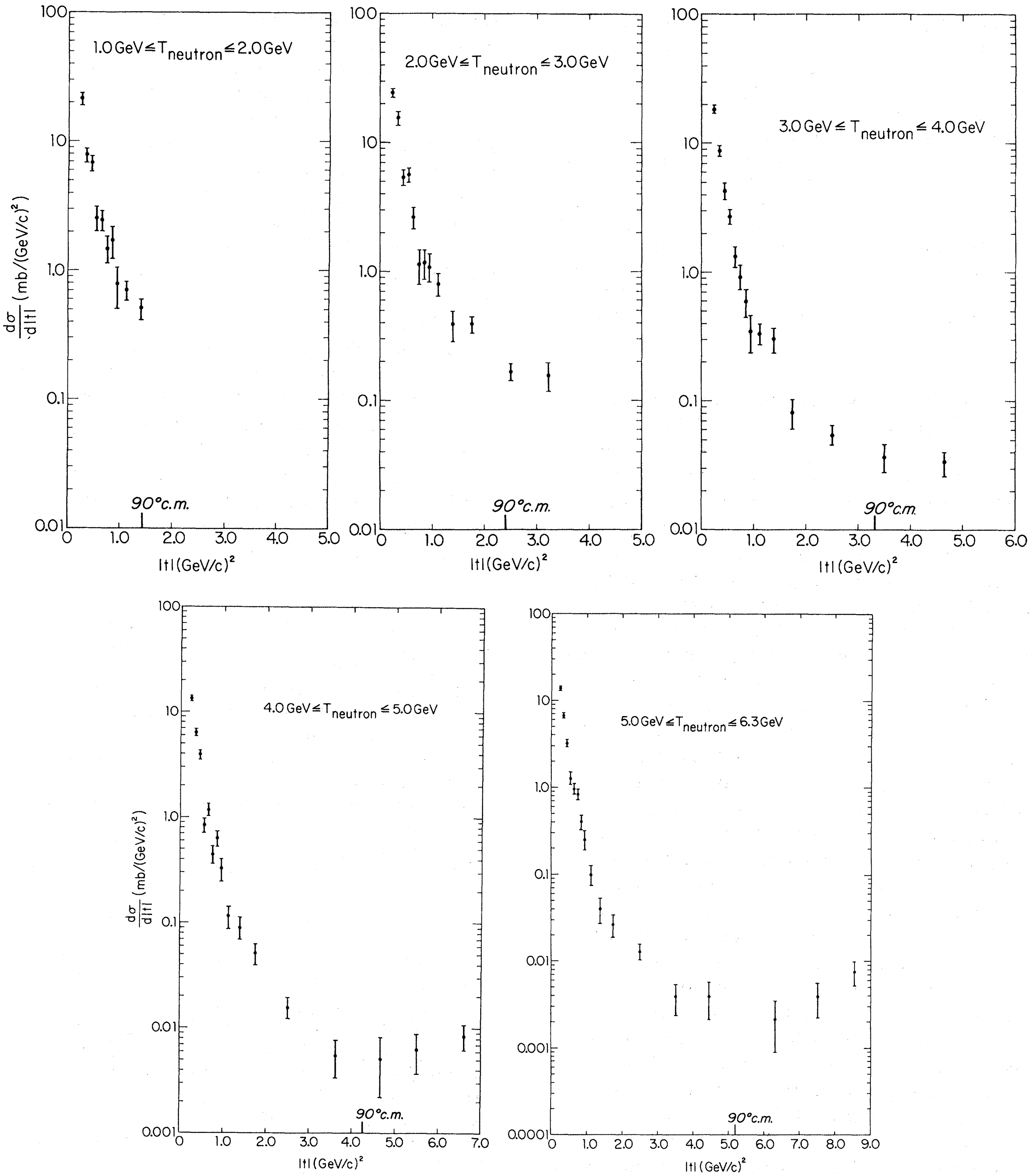

FIG. 2. Neutron-proton differential cross sections versus $|t|$.

shown in Table I.

We first observe that, as expected by our general understanding of high-energy elastic scattering in the presence of a large inelastic cross section, there is a strong diffraction peak at all energies. The peak has a roughly exponential behavior.

We have fit the region $0.2 < |t| < 0.6$ $(\mathrm{GeV}/c)^2$ with the form $d\sigma/d|t| = A \exp(b|t|)$, and b is given in Table I. According to recent data of

Table I. Values of the slope of the diffraction peak for each energy interval.

Incident kinetic energy range (GeV)	p^* average (Momentum in center of mass) (GeV/c)	b [(GeV/c)$^{-2}$]
1.0–2.0	0.851	-6.321 ± 0.647
2.0–3.0	1.096	-5.527 ± 0.463
3.0–4.0	1.287	-6.655 ± 0.432
4.0–5.0	1.460	-7.720 ± 0.411
5.0–6.3	1.612	-7.562 ± 0.391

Clyde et al.,[7] the values of $-b$ for proton-proton scattering at 2.2, 4.1, and 6.2 GeV are 6.50 ± 0.03, 7.44 ± 0.04, and 7.69 ± 0.04 (GeV/c)$^{-2}$. The neutron-proton and proton-proton diffraction-peak slopes have about the same values except perhaps at the lower energies. The slopes in the energy region from 2 to 6 GeV indicate a shrinkage of the diffraction peak quite similar to proton-proton scattering.

The following observations may be made on the large-angle region. The differential cross section deviates from exponential and begins to flatten out as $\theta^* = 90°$ is approached. It is roughly flat, that is, isotropic near 90°, and the minimum in the differential cross section is at or just beyond 90°. The isotropy near 90° is predicted both by the statistical model[8] and by the model of Wu and Yang.[9] Beyond 90°, $d\sigma/d|t|$ increases even though the values of $|t|$ are very large. This leads to the idea that t is no longer the meaningful parameter because the neutron and proton are exchanging their charges, and u (the square of four-momentum transfer from the incident neutron to the recoil proton) is the relevant parameter. Since $|u| = 4p^{*2} - |t|$, $|u|$ is decreasing as θ^* approaches 180°. In this experiment we used a slightly different technique to measure the region near 180°, but that data are not completely analyzed yet. Comparison with other data[1,2] near 180° indicates that our differential cross section will rise roughly monotonically into the charge-exchange peak. However, in the backward-angle regions presented in Fig. 2, $d[\ln(d\sigma/d|u|)]/d|u|$ is about 0.6 (GeV/c)$^{-2}$ compared to 40 or 50 (GeV/c)$^{-2}$ at 180°.

The statistical model predicts an exponential decrease with the center-of-mass total energy W^* of the form $(d\sigma/d\Omega^*)_{90°} = A \exp(-gW^*)$. We found g to be 3.73 ± 0.38 (GeV)$^{-1}$. If we fit the decrease with a power of W^*, namely $(d\sigma/d\Omega^*)_{90°} = CW^{*-N}$, then $N = 11.04 \pm 1.15$. Finally, Clyde et al.[7] give the proton-proton differential cross section at 90° as 0.45 ± 0.01, 0.016 ± 0.0009, and $0.000\,78 \pm 0.000\,04$ mb/(GeV/c)^2 at 2.2, 4.1, and 6.2 GeV.[10] Interpolation of our data yields 0.32 ± 0.05, 0.017 ± 0.006, and 0.0014 ± 0.0008 mb/(GeV/c)^2 at these energies.

We find no clear evidence for a second forward peak in the neutron-proton system. There are some ambiguous indications as can be seen from Fig. 2, which should be resolved when the remainder of our data are analyzed.

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