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Neutron-Proton Elastic Scattering from 70 to 400 GeV/*c*

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We have measured neutron-proton elastic-scattering cross sections for the range $0.15 \lesssim -t \lesssim 3.6$ (GeV/c)^2. The logarithmic slope parameter is found to be consistent with existing proton-proton parametrizations. The data also exhibit a dip in the cross section near $-t \approx 1.4$ (GeV/c)^2 for incident neutron momenta above 200 GeV/c. Differences between n-p and p-p cross sections are noted in the region $0.7 \lesssim -t \lesssim 1.4$ (GeV/c)^2.

We report results of an experiment at Fermi National Accelerator Laboratory to measure neutron-proton elastic scattering using techniques developed in previous experiments.[1,2] Differential cross sections were measured in the range[3] of 70 to 400 GeV/c with an incident neutron beam. Squared four-momentum transfers from 0.15 to ~3.6 (GeV/c)^2 were covered, with particular attention being paid to the region $-t \approx 1.4$ (GeV/c)^2 where structure has been previously reported[4,5] in p-p elastic scattering.

A schematic diagram of the experiment is shown in Fig. 1. The neutron beam was incident upon a liquid hydrogen target, 30.5 cm long and 5.1 cm in diameter. The beam size was varied from 5 to 25 mm depending on the desired intensity. Lead filters reduced the photon contamination in the beam to < 1%, and separate measurements of the K_L contamination showed it to be negligible except possibly below 100 GeV/c. The recoil-proton momentum and scattering angle were measured by a spectrometer consisting of four wire-spark-chamber modules SC1–SC4, each with X-Y-U-V magnetostrictive readout planes, and a 105-cm×100-cm analyzing magnet with a 15.1-cm gap. The strength of the magnetic field was 7.6 kG for the low-$|t|$ data [$0.15 \leqslant |t| \lesssim 1.0$ (GeV/c)^2] and 12.5 kG for the high-$|t|$ data [$0.8 \lesssim |t| \lesssim 3.6$ (GeV/c)^2]. Part of the trigger requirement was a fast coincidence between scintillation counters P_1, P_2, and P_3 which indicated that a charged particle had traversed the spectrometer. The scattered neutron was required to interact in a neutral-particle de-

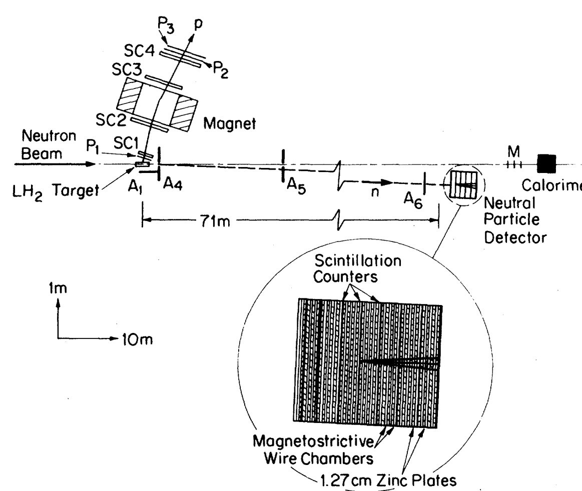

FIG. 1. Schematic layout of the experimental apparatus. The inset shows the neutron detector in more detail.

tector and produce a charged-particle shower. The detector contained thirty wire spark chambers, 28 zinc plates, and six scintillation counters (see inset of Fig. 1) and was placed 71 m downstream of the hydrogen target. We determined the interaction point to an accuracy ~2 mm full width at half-maximum by locating the vertex of the charged-particle shower in the chambers. The neutron-scattering angle was then defined by the interaction point in the neutral-particle detector and a point within the illuminated part of the hydrogen target on the proton trajectory. The second part of the triggering requirement was a fast coincidence between any two of the six scintillation counters, indicating that at least one charged particle had passed through the detector. Veto counters $A_1 \ldots A_6$, not all of which are shown in Fig. 1, nearly surrounded the target and greatly reduced the trigger rate from inelastic events. All of these except A_6 were scintillator-lead sandwiches and so were sensitive to photons. A counter telescope M and a total-absorption calorimeter were used to monitor the beam flux.

All kinematic variables were measured except for the momenta of the incident and scattered neutrons. Thus momentum and energy conservation allowed a two-constraint fit to the hypothesis of n-p elastic scattering. The fitting program calculated the unmeasured momenta and a χ^2 for the fit. Events with $\chi^2 < 10$ were considered to be elastic and were binned according to the incident neutron momentum and the squared four-momentum transfer, t.

Various corrections have been applied to the data. We calculated the geometric acceptance using Monte Carlo techniques. Inelastic background corrections, as estimated from χ^2 distributions, amounted to less than 3% at small $|t|$ and less than 35% at large $|t|$. Corrections for nuclear absorption of the recoil proton ranged from 2% to 4%. Target-empty corrections were negligible. It is important to note that the neutron-detection efficiency, which was about 65%, does not significantly affect the t dependence of the measured cross sections because the energy of the scattered neutron differs from that of the incident neutron by at most 2%.

The resolution in t is independent of the incident neutron momentum and is determined by multiple Coulomb scattering of the recoil proton and the resolution of the proton spectrometer. The uncertainty in t was approximately 1% for all values of t. The resolution of the incident neutron momentum p is t dependent since the neutron scattering angle is correlated with the recoil-proton scattering angle. At 200 GeV/c and $|t| = 1.4$, the uncertainty in momentum was less than 6 GeV/c.

Both low-$|t|$ and high-$|t|$ data were collected in each of two running periods which were spaced six months apart. In principle, it is possible to use either the telescope M or the total-absorption calorimeter to provide relative normalization between data sets. However, because of possible shifts in the energy spectrum due to different production angles of the neutral beam, the data sets were normalized relative to each other by tying the data together in various overlap regions. This typically involved five data points per data set and we estimate the uncertainty in this procedure to be approximately 4%. After the data were combined, the overall normalization was calculated by fitting the data by the form $d\sigma/d|t| = A\exp(Bt + Ct^2)$ in the range $0.17 \leq |t| \leq 0.7$ and extrapolating to $t = 0$. The intercept was then adjusted to the optical-theorem point as given by

$$\frac{d\sigma(t=0)}{d|t|} = \frac{1}{16\pi}\sigma_T^{\,2}(1+\rho^2). \tag{1}$$

The values of σ_T used were calculated from a fit of n-p total-cross-section data given by Murthy *et al.*[6] If we assume that the ratio of the real to imaginary parts of the forward-scattering amplitude, ρ, for n-p elastic scattering is approximately the same as that for p-p scattering,[7] the contribution of the ρ^2 term in Eq. (1) is negligible. The uncertainty in the overall normalization is estimated to be $^{+5}_{-15}\%$, mainly due to the uncertainty in the extrapolation to $t = 0$.

Of the 1.1×10^6 triggers recorded, approximately 25% were elastic events. The data are presented in Fig. 2 for seven incident-momentum bins. The errors shown include the statistical and the correction-factor uncertainties but not the uncertainty in the overall normalization. The incident momentum attached to each graph is that of the bin center.

The data exhibit the usual diffraction peak which shrinks with increasing energy. Using the fit by $A\exp(Bt + Ct^2)$ described above, we have evaluated the logarithmic slope at $-t = 0.2$ (GeV/c)^2. The results are shown in Fig. 3 along with previous measurements for n-p [8,9] and p-p [10,11] elastic scattering. The slope parameters have been plotted as a function of s, the squared center-of-mass energy. Our slopes agree with corresponding p-p data and also with the Reggeized global absorp-

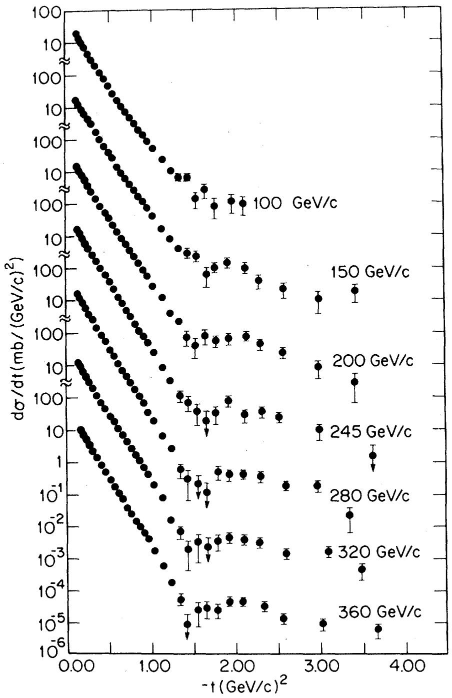

FIG. 2. Neutron-proton differential cross sections in in millibarns per $(\mathrm{GeV}/c)^2$ for seven incident-momentum bins. The momenta indicated are the center of the bins.

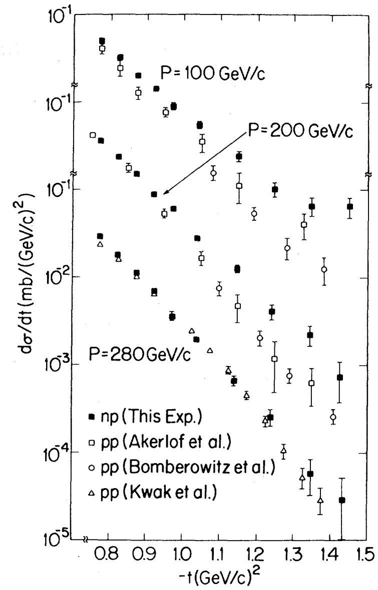

FIG. 4. Neutron-proton differential cross sections in millibarns per $(\mathrm{GeV}/c)^2$ for 75–125, 175–225, and 265–300 GeV/c bins. Also shown are the 200-GeV/c proton-proton data of Akerlof *et al.* (Ref. 4), preliminary data from Bomberowitz *et al.* (Ref. 13), and the 280-GeV/c p-p data of Kwak *et al.* (Ref. 5).

tion model of Kane and Seidl.[12]

The data also show the gradual evolution of a dip in the cross section near $-t \approx 1.4$ $(\mathrm{GeV}/c)^2$ as the incident neutron energy increases. While the dip is similar to that observed in p-p data, we find that the n-p cross sections are generally higher in this region.

Figure 4 compares our data with existing p-p elastic-scattering data from Fermilab[4,13] at 100 and 200 GeV/c. At the lower momentum, the cross sections are comparable out to $-t \approx 0.8$ $(\mathrm{GeV}/c)^2$. At larger t, they begin to diverge, with the n-p cross sections approximately 3 times the p-p cross section near $-t \approx 1.25$ $(\mathrm{GeV}/c)^2$. This difference extends to $-t \approx 1.4$ $(\mathrm{GeV}/c)^2$. At 200 GeV/c, the cross sections for n-p and p-p remain comparable out to $-t \approx 0.95$ $(\mathrm{GeV}/c)^2$, beyond which they begin to diverge. As in the 100-GeV/c data, the n-p cross section is 3 times the p-p data near $-t \approx 1.25$ $(\mathrm{GeV}/c)^2$. In order to see if the n-p data exhibit a strong energy dependence we have also binned the data for the incident momentum range 200 to 240 GeV/c. The cross sections remain unchanged out to $-t \approx 1.3$ $(\mathrm{GeV}/c)^2$.

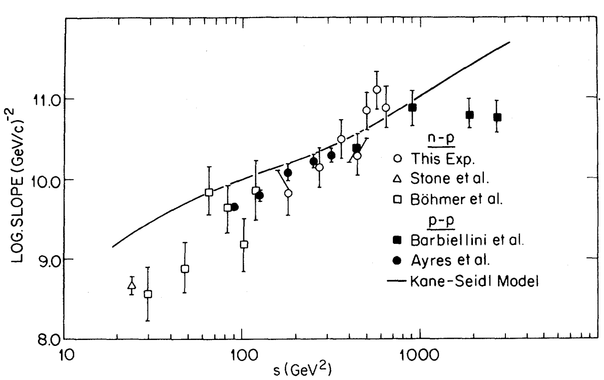

FIG. 3. Logarithmic slope parameter plotted as a function of the center-of-mass energy squared, s, for n-p and p-p elastic scattering. The solid curve is a prediction from Kane and Seidl (Ref. 12).

Also in Fig. 4, our 280-GeV/c data are compared to intersecting-storage-ring data[5] at a lab equivalent energy of 282 GeV/c. We find that the n-p and p-p cross sections are in good agreement out to $-t \approx 1.2$ $(\mathrm{GeV}/c)^2$. In a Regge model, the difference between n-p and p-p elastic scattering is caused by a change in the sign of the ρ and A_2 isovector exchange amplitudes. The magnitude of these amplitudes should decrease with increasing energy. Our results indicate just such an effect. As s increases, the n-p and p-p cross sections are comparable out to larger values of t.

By 280 GeV/c, the contribution of the ρ and A_2 would seem to be quite small. In most Regge models, the n-p cross sections are equal to or less than the p-p cross sections in this region of t. The fact that the n-p cross sections are greater indicates that some amplitudes, such as the net helicity-flip amplitudes, may not be correctly understood in this region.

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Production of Large-Transverse-Momentum Jets in Photon-Photon Collisions

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We predict a new source of jet structure in e^+e^- colliding-beam experiments arising from photon-photon collisions. These jets are produced with a sizable fraction of the total observable hadronic rate and have unmistakable signatures. Observations of these jets would provide important tests of the contributions of three classes of hard-scattering mechanisms: quark exchange in $\gamma\gamma \to q\bar{q}$, gluon exchange in qq and $q\bar{q}$ scattering, and constituent-interchange processes with a characteristic $p_\perp^{-6}$ behavior.

Photon-photon collisions in e^+e^- storage rings become increasingly important as the energy of the storage rings increases. The dominant part of the cross section for $e^+e^- \to e^+e^-$ + hadrons arises from nearly on-shell photons emitted at small angles to the beam and increases logarithmically with energy:

$$\frac{d\sigma}{d\mathfrak{M}^2}(e^+e^- \to e^+e^- X) \approx \left(\frac{\alpha}{\pi}\ln\frac{s}{4m_e^2}\right)^2 \ln\left(\frac{s}{\mathfrak{M}^2}\right)\frac{\sigma_{\gamma\gamma\to X}(\mathfrak{M}^2)}{\mathfrak{M}^2} \tag{1}$$

for $m_e^2/s \to 0$, $s = (p_e + p_{e^-})^2$, and $s \gg \mathfrak{M}^2 = (p_{\gamma_1} + p_{\gamma_2})^2$. A simple vector-dominance prediction for the hadronic photon-photon cross section gives $\sigma(e^+e^- X) \approx 15$ nb for $E_e = 15$ GeV and $\mathfrak{M}^2 \geq 1$ GeV^2. This is to be compared with the single-photon cross section $\sigma(e^+e^- \to \gamma \to X) = (4\pi\alpha^2/3s)R \approx (0.1\text{ nb})R$.[1]