COMPARISON OF HIGH-ENERGY NEUTRON-PROTON AND PROTON-PROTON ELASTIC SCATTERING*

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Neutron-proton and proton-proton elastic scattering are compared in the momentum range from 3 to 7 GeV/c. At the same incident momenta the np and pp diffraction peaks have similar slopes, and both peaks shrink with increasing momentum. Over this momentum range the 90° np cross section is 1.1 ± 0.1 times the 90° pp cross section. Differential cross sections for nucleon-nucleon scattering with isospin 0 are compared with those for isospin 1.

In the preceding Letter,[1] we have reported new data on neutron-proton elastic scattering from 3 to 7 GeV/c. The purpose of this Letter is to compare np and pp elastic scattering in that momentum range.

For high energies and small angles, where the elastic scattering is mainly diffractive, the width of the diffraction peak is a measure of the interaction radius. We find that between 3 and 7 GeV/c the widths for np scattering agree well with those for pp scattering, thus supporting the idea that the distribution of hadronic matter in the neutron and proton are very similar. In the diffraction region, which we define as $|t| \leq 0.4$ $(\text{GeV}/c)^2$, σ can be represented by the equation $\sigma = A\exp(-B|t|)$. Here t is the square of the four-momentum transfer, and σ is the differential cross section, usually called $d\sigma/dt$. Since the np data are absolutely normalized by using the optical theorem and the total np cross section (assuming no real part for the np forward scattering cross section), A is not determined from our np data, and no comparison is made here. In Fig. 1, we compare the values of B for pp[2,3] and np scattering. In this figure we have also plotted a recent np bubble chamber measurement by Besliu et al.[4] We see the np and pp exponential slopes B agree within the errors of the np points. Thus, even at these incident momenta the small-angle shape of the pp and np elastic cross sections is the same.

At large angles[5] and particularly in the 90° region, however, it is not clear a priori how the high-energy behavior of the np system will compare with that of the pp system. For example, Wu and Yang[6] have speculated that at 90° and high energies the np cross section will be one-half of the pp cross section. The difficulty in making a definite prediction at large angles, even at very high energies, is caused by the lack of a simple model and by the large number of independent amplitudes. For each isospin state ($I = 1$ and $I = 0$) there are five independent scattering amplitudes, which have definite symmetry properties

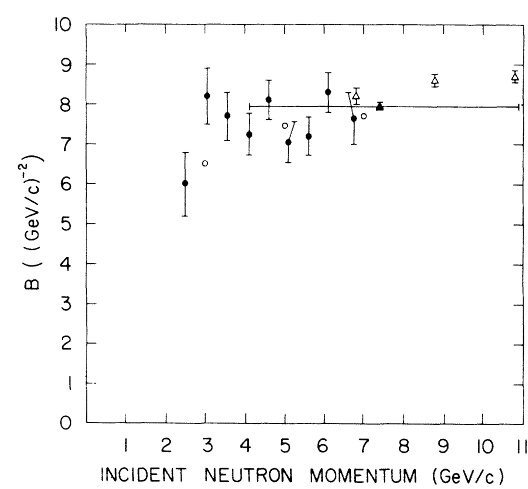

FIG. 1. Comparison in np and pp scattering of the parameter B in the equation $\sigma = A\exp(-B|t|)$ for $|t| \leq 0.4$. σ is the differential cross section and t is the square of the four-momentum transfer. B for the np system is given by the solid circles (this experiment) and the solid triangle (Ref. 4). The pp values of B are represented by the open circles (Ref. 2) and the open triangle (Ref. 3).

about 90° determined by the generalized Pauli principle. The corresponding amplitudes for the two isospin states cannot be directly equated, even at very high energies, because of these symmetry properties. For example, if a classification into triplet and singlet total spin states is used, the singlet spin state is antisymmetric in space for $I=0$ and is symmetric in space for $I=1$. In this Letter, we compare the large-angle np and pp differential cross section, extract the $I=1$ and $I=0$ contributions, and make an attempt at a simple model. However it is not possible to produce a unique model for this region.

To compare the np and pp differential cross sections at 90° we define the ratio $R=\sigma^{np}(90°)/\sigma^{pp}(90°)$. The values of $\sigma^{pp}(90°)$ were obtained from Ref. 2 and Akerlof et al.[7] The values of R are listed in Table I, and we find the average value of R from 4 to 7 GeV/c is $1.10_{-0.10}^{+0.13}$. At the highest momenta R rises above 1.0, but the errors are large here and probably the only really significant number is the average value of R stated above.[8] Thus we conclude that $\sigma^{np}(90°)$ is equal to or somewhat greater than $\sigma^{pp}(90°)$. A recent theory of Krisch[9] on pp elastic scattering predicts $R=0.05$, but this theory applies primarily to the region of incident momenta above 8 GeV/c.

Table I. Values of R.

Momentum (GeV/c)	R	Error in R
3.0	0.7	+0.15, −0.1
3.6	1.2	+0.3, −0.2
4.1	1.0	+0.2, −0.15
4.6	0.8	+0.2, −0.15
5.1	1.2	+0.4, −0.3
5.6	1.3	+0.4, −0.4
6.1	1.4	+0.6, −0.5
6.8	2.9	+1.5, −1.4

As discussed in the preceding paper, the nucleon-nucleon scattering amplitude can be written as a matrix in isospin space. The differential cross sections can be written[10]

$$\sigma^{pp}=\tfrac{1}{4}|M_{ss}{}^1|^2+\tfrac{1}{4}|M_{00}{}^1|^2+\tfrac{1}{2}|M_{11}{}^1|^2+\tfrac{1}{2}|M_{10}{}^1|^2+\tfrac{1}{2}|M_{01}{}^1|^2+\tfrac{1}{2}|M_{1-1}{}^1|^2,$$

$$\sigma^{np}=\tfrac{1}{16}|M_{ss}{}^1+M_{ss}{}^0|^2+\tfrac{1}{16}|M_{00}{}^1+M_{00}{}^0|^2+\tfrac{1}{8}|M_{11}{}^1+M_{11}{}^0|^2+\tfrac{1}{8}|M_{10}{}^1+M_{10}{}^0|$$
$$+\tfrac{1}{8}|M_{01}{}^1+M_{01}{}^0|^2+\tfrac{1}{8}|M_{1-1}{}^1+M_{1-1}{}^0|^2,$$

where the amplitudes M are defined in Ref. 10 and the superscripts 1 and 0 designate the $I=1$ and $I=0$ states. $M_{ss}{}^1, M_{01}{}^1, M_{10}{}^1$ are symmetric about 90° and $M_{00}{}^1, M_{11}{}^1, M_{1-1}{}^1$ are antisymmetric about 90°. The corresponding $I=0$ amplitudes have the opposite symmetry. We can define an $I=0$ differential cross section:

$$\sigma^0=\tfrac{1}{4}|M_{ss}{}^0|^2+\tfrac{1}{4}|M_{00}{}^0|^2+\tfrac{1}{2}|M_{11}{}^0|^2+\tfrac{1}{2}|M_{01}{}^0|^2+\tfrac{1}{2}|M_{10}{}^0|^2+\tfrac{1}{2}|M_{1-1}{}^0|^2.$$

Then because of the symmetries of the various amplitudes,[11]

$$\sigma^0(\theta)=2[\sigma^{np}(\theta)+\sigma^{np}(\pi-\theta)]-\sigma^{pp}(\theta). \qquad (1)$$

At $\theta=90°$, $R=1.1\pm0.1$ gives $\sigma^0(90°)=(3.4\pm0.3)\times\sigma_1(90°)$ for the region from 4 to 7 GeV/c. This result has a simple interpretation if we assume that only contributions from central forces are important near 90°. With this assumption, at $\theta=90°$ the only nonzero amplitudes are $M_{ss}{}^1$, $M_{11}{}^0$, and $M_{00}{}^0$ with $M_{11}{}^0=M_{00}{}^1$. Then at 90°, $\sigma^0=\tfrac{3}{4}|M_{00}{}^0|^2$ and $\sigma^1=\tfrac{1}{4}|M_{ss}{}^1|^2$ so that $|M_{00}{}^0|^2=(1.1\pm0.1)|M_{ss}{}^1|^2$. This says that the symmetric parts of the $I=1$ and $I=0$ amplitudes are almost equal at 90°, a plausible result at high energies.

In Fig. 2, we have plotted σ^0 and σ^1 at 5 GeV/c based on the pp data of Clyde,[2] our np data from the preceding Letter, and Eq. (1). For $\cos\theta>0.8$ we have neglected $\sigma^{np}(\pi-\theta)$ compared with $\sigma^{np}(\theta)$, because $\sigma^{np}(\pi-\theta)$ for $\cos\theta>0.8$ is less than $0.1\sigma^{np}(\theta)$. We observe that σ^0 is about equal to

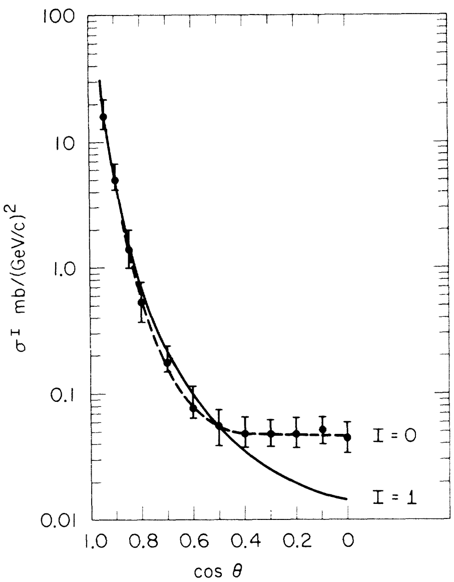

FIG. 2. The differential cross section σ^I at 5 GeV/c plotted against the cosθ in the c.m. system. σ^1 is the $I=1$ or pp differential cross section. σ^0 is the $I=0$ differential cross section defined in the text.

σ^1 at small angles, but becomes three times as large as 90° is reached.

The relative behavior of σ^0 and σ^1 is similar at the other momenta studied in this experiment. At the lower momenta there is some suggestion of structure near $|t|=0.6$, as noted in the preceding Letter. Since it is known that σ^1 falls off very smoothly with increasing $|t|$ (Ref. 2), any structure in σ^{np} must come from σ^0. At small angles the near equality of σ^1 and σ^0 is to be expected because of the approximate equality of the total cross section for np and pp scattering and because the backward np peak is much smaller than the forward peak. This behavior can be expected to continue at high energies. For the large-angle region ($|\cos\theta|<0.5$), where $\sigma^0>\sigma^1$, it is not so clear what to expect at higher energies. If $\sigma^0(90°)$ becomes equal to $\sigma^1(90°)$ in the high-energy limit then $\sigma^{np}(90°)\rightarrow\frac{1}{2}\sigma^{pp}(90°)$. On the other hand, if $\sigma^{np}(90°)$ and $\sigma^{pp}(90°)$ remain approximately equal in this limit, then $\sigma^0(90°)\rightarrow 3\sigma^1(90°)$. It would be very interesting to extend the measurements in the large-angle region to higher energies to investigate this behavior.

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