ELASTIC AND ELECTROMAGNETIC PROTON INTERACTIONS AT 3 TeV*

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Summary

In the present paper we present the results of a line scan, in nuclear emulsion, of protons of average energy 3 TeV. No elastic scatters were detected in the scanned length of 594 cm. We calculate the probability of detecting an elastic scatter in emulsion, and hence that the proton–proton elastic cross section at 3 TeV is $\lesssim$ 5 mbn.

Five examples of proton direct pair production have been found in the above path length. We show that this result is consistent with the predictions of quantum electrodynamics.

Introduction

At energies up to 30 GeV elastic proton–proton scattering has been extensively studied. Since this phenomenon is probably the most fundamental nuclear process, it is of interest to compare the p–p elastic cross section at these energies with that at the higher energies available in cosmic radiation. This is particularly so, since it has been suggested recently (see Morrison 1963) that this cross section is still appreciable at cosmic ray energies.

In the present paper we present the results of a line scan of 594 cm of high energy proton tracks in nuclear emulsion. Our result is that no elastic scatter was detected. From this we calculate an approximate upper limit for the p–p elastic cross section. At the same time we present evidence of proton trident production, that is, direct pair production by the Coulomb field of the proton. We claim five such events in the above path length giving a cross section that is in agreement with the predictions of quantum electrodynamics.

The Experiment

The events used in this analysis were from the Sydney 10 and 20 litre stacks (see Brisbout *et al.* 1961; McCusker and Peak 1964) and the Minnesota 11 litre stack. Starting from the high energy proton-induced interactions found in these stacks, the incident protons were line scanned to their point of entry into the stack. Every track, with length $\geqslant$ 10 microns, that appeared to start on the proton track was checked to see if it could be attributed to an elastically scattered proton. Each track from which a pair emanated was retraced, forward and backward, by different scanners to verify that it was in fact the proton track.

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Elastic Proton–Proton Scattering

The differential elastic p–p cross section $\mathrm{d}\sigma/\mathrm{d}t$ in the region up to 30 GeV has been shown to fit the relation

$$\mathrm{d}\sigma/\mathrm{d}t \propto \mathrm{e}^{At}$$

in the diffraction region, that is, $-t \lesssim 1\,(\mathrm{GeV}/c)^2$, where $-t$ is the square of the 4-momentum transfer, and A is a slowly varying function of energy (see Cocconi *et al.* 1961; Bull and Garbutt 1963).

If we assume that this relation is still applicable up to 3 TeV and we extrapolate the experimental results, listed by Morrison (1963), to this energy, then we obtain $A \sim 20$. Thus the average 4-momentum transfer is $-t \sim 0\cdot05\,(\mathrm{GeV}/c)^2$. This corresponds to the scattered nucleon having a kinetic energy of about 30 MeV.

The Detection of Elastic Scatters in Emulsion

At the mean proton energy, for our events, of 3 TeV we expect the average kinetic energy of the scattered proton to be about 30 MeV. Then, for the case of proton–nucleus elastic scattering, in addition to a very small angle deviation (which in general is not detectable), we expect the following:

(1) *p–p scattering*

- (*a*) One heavy track at about 90°, plus sometimes small nuclear excitation, or
- (*b*) nuclear excitation only, or
- (*c*) no visible effect.

(2) *p–n scattering*

- (*a*) Some nuclear excitation, or
- (*b*) no visible effect.

Thus only those scatters of types 1(*a*), 1(*b*), and 2(*a*) are detectable in emulsion. This is, of course, ignoring the small effect of charge exchange scattering.

(*a*) *The Probability of Seeing the Scattered Proton*

The kinetic energy E of a scattered nucleon is given by

$$E = \frac{p_{\mathrm{c}}^2}{m}\cdot(1-\cos\theta_{\mathrm{c}}), \tag{1}$$

where p_{c} is the momentum, and θ_{c} the angle of emission, in the centre-of-mass system, of the nucleon of mass m. For nucleon scattering $\lesssim 60$ MeV, θ_{c} is approximately isotropically distributed. Thus from (1) we have that, on average, the nucleon loses half its energy in each subsequent scatter in the nucleus. Now the detection limit for a scattered track emerging from a nucleus, as stated above, is a track length of $\geqslant 10$ microns, that is, for protons in emulsion $E \geqslant 1$ MeV. However, since at each scatter the proton energy is reduced by a factor of two, we can only detect the proton if the number of collisions n it undergoes while emerging from the nucleus is such that $E_0/2^n \geqslant 1$; where E_0 is the proton energy after its initial scatter. That is,

$$n \leqslant \log E_0/\log 2.$$

Thus for $E_0 = 30$ MeV, we require $n \leqslant 5$.

At 30 MeV the average elastic proton–nucleon cross section for nuclear matter is about 200 mbn. It can be shown that the average distance a scattered proton travels in the nucleus is about $0\cdot 82R$ cm, where R is the radius of the average emulsion nucleus, and hence that the proton suffers, on average, $7\cdot 5$ collisions while emerging from the nucleus. Thus the probability of detecting a scattered proton is

$$\sum_{r=0}^{5} \frac{(7\cdot 5)^r \mathrm{e}^{-7\cdot 5}}{r!} \sim 30\%.$$

(b) The Probability of Nuclear Excitation

The experimental results at lower energy suggest that at 3 TeV the distribution of kinetic energy of the scattered nucleon is

$$N(E)\mathrm{d}E\, \mathrm{e}^{-E/30}\,\mathrm{d}E,$$

where E is in MeV. The number of observable heavy tracks emitted, N_{b}, is given by $E \approx (40+40N_{\mathrm{b}})$. Those events that have not emitted a detectable scattered proton will have given almost all their energy to the nucleus. Thus the distribution of N_{b} for these events will be

$$N(N_{\mathrm{b}})\mathrm{d}N_{\mathrm{b}}\, \mathrm{e}^{-(4/3)N_{\mathrm{b}}}\,\mathrm{d}N_{\mathrm{b}}.$$

Hence the fraction of events with $N_{\mathrm{b}} \geqslant 1$ is 25%.

For the neutron scatters, we must also consider the events where an unobserved neutron is emitted and some excitation occurs. Then, making allowance for the energy retained by the neutrons and calculating as above, we obtain the result that 23% of these scatters will show observable nuclear excitation. Thus the total probability of detecting an elastic scatter is given by

(fraction of protons)(fraction of protons emitted+fraction not emitted× probability of observable excitation)

+(fraction of neutrons)(fraction of neutrons emitted×probability of observable excitation+fraction not emitted×probability of observable excitation),

that is,

$$0\cdot 45(0\cdot 30+0\cdot 70\times 0\cdot 25)+0\cdot 55(0\cdot 30\times 0\cdot 23+0\cdot 70\times 0\cdot 25) = 0\cdot 35.$$

Results

The total length of track scanned was 594 cm, and in this length no elastic scatter was detected. The probability that such a result is consistent with a given mean free path λ cm is $P = \mathrm{e}^{-594/\lambda}$.

In Table 1 we give, for various p–p elastic cross sections, the corresponding mean free path in emulsion, the mean free path expected for our detection probability of 35%, and the deduced probability that this is consistent with no scatters in 594 cm. The values of $\lambda_{\text{emulsion}}$ were obtained from the data of Barashenkov (1954).

TABLE 1

ELASTIC CROSS SECTIONS AND CORRESPONDING MEAN FREE PATHS IN EMULSION

$(\sigma_{\text{p-p}})_{\text{el.}}$ (mbn)	$\lambda_{\text{emulsion}}$ (cm)	$\lambda_{\text{expected}}$ (cm)	P (%)
10	64	183	4
5	105	300	14
4	128	366	20
3	168	480	29
2	250	715	43

Thus we see that from this experiment we can say that the p–p elastic cross section is most likely not greater than about 5 mbn, but how much less must await further experiment.

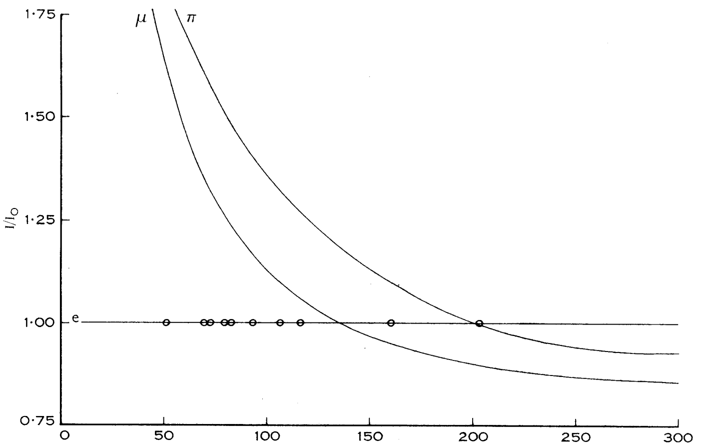

Fig. 1.—The grain density v. scattering curves for pions, muons, and electrons, together with the experimental values for the pairs produced by high energy protons.

Proton Trident Production

In the 594 cm path length we found five events with the following characteristics:
(1) a pair of tracks, of minimum ionization, materialized on the initial proton track;
(2) the angle between the two tracks, and the angle between their mean position and the proton direction, were both of the order of a few milliradians.

Relative scattering measurements were carried out on each produced track with respect to the proton track, and the results are shown in Figure 1. We see that most of the events are clearly electrons. Thus, we conclude that each set of tracks is an electron pair and that these events are in fact all examples of trident production, that is, the direct production of an electron pair by the Coulomb field of the proton. Our result then is that the mean free path in emulsion for direct pair production by protons,* at our median Castagnoli energy of $2\cdot 8$ TeV, is

$$\lambda = 594/(5\pm\sqrt{5}) = 120^{+100}_{-40}\ \text{cm}.$$

Comparison with Theory

The cross section for direct pair production by a charged particle, ignoring screening effects, is given by Block, King, and Wada (1954) as

$$\sigma = \frac{28}{27\pi}\left(\frac{r_0 Z}{137}\right)^2\left[\ln^3\left(\frac{E_0}{mc^2}\right)-\frac{44}{7}\ln^2\left(\frac{E_0}{mc^2}\right)+\left\{\frac{54}{7}+\frac{88}{7}\ln 2-3\ln^2 2\right\}\ln\left(\frac{E_0}{mc^2}\right)\right.$$
$$\left.-\frac{54}{7}-\frac{52}{7}\ln 2-\frac{44}{7}\ln^2 2+2\ln^3 2+\ldots\right],$$

where r_0 is the classical electron radius, Z is the average charge of the target nucleons, E_0 is the total incident energy, and m is the mass of the charged particle. This formula is applicable in the region where

$$m_e c^2 < E_{e+}, \qquad E_{e-} < \left(\frac{E_0}{mc^2}\right) m_e c^2,$$

with m_e the rest mass of an electron, and E_{e+}, E_{e-}, the energies of electrons of the pair.

Thus for our data we have

$$\tfrac{1}{2}\ \text{MeV} < E_{e+}, \qquad E_{e-} < 1500\ \text{MeV}.$$

It can be seen from Figure 1 that all the electrons clearly satisfy this criterion. Then for $E_0 = 2\cdot 8$ TeV we have $\sigma = 13\cdot 7\times 10^{-26}$ cm²/nucleus for emulsion. Now Rovenhall (1950) gives the effect of screening in emulsion at $2\cdot 8$ TeV as about 8%. This then implies that the expected cross section in emulsion is $= 12\cdot 6\times 10^{-26}$ cm²/nucleus. Thus the mean free path is expected to be about 100 cm, which is in agreement with our value of 120^{+100}_{-40} cm.

Conclusion

594 cm of very high energy proton track have been line scanned. No elastic scatters were detected, suggesting that the proton–proton elastic cross section at about 3 TeV is $\lesssim 5$ mbn.

Five trident events were found, implying a mean free path in emulsion of 120^{+100}_{-40} cm. This is in agreement with the predictions of quantum electrodynamics and thus indicates its validity up to energies of several TeV.

* Of course for protons pseudo trident production (i.e. bremsstrahlung pairs materializing on the track), which is relatively common for high energy electrons, is negligible since the total proton bremsstrahlung cross section is negligible.

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