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ELASTIC AND QUASI-ELASTIC COLLISIONS OF PROTONS WITH MOMENTA BETWEEN 9 AND 25 Gev/c

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The analysis of the interactions of ultrarelativistic[1] cosmic-ray nucleons has provided some evidence that these particles often emerge from collisions against nucleons at rest with little loss of energy (quasi-elastic collisions). It has appeared difficult to reconcile this behavior with the Fermi statistical model, which was the most commonly accepted description of the ultrarelativistic nucleon-nucleon interaction. Recently, however, theoretical arguments have been advanced[2,3] for expecting quasi-elastic collisions.

The CERN 25-Gev proton synchrotron is an intense source of monochromatic ultrarelativistic protons with which phenomena of this kind can now be quantitatively studied. This Letter describes the results of a first series of experiments in which quasi-elastic collisions have actually been observed.

The proton beam utilized was the internal circulating beam. These protons are well collimated and of well-defined energy. Their energy spread is due partly to the ionization losses experienced in the multiple traversals of the target (~100 Mev) and partly to the fluctuations of the top energy from burst to burst, also of the same order of magnitude. The internal target was a Be foil 50 μ thick and the region of the target hit by the protons was roughly circular, about 1 cm in diameter.[4] The protons, scattered by the target at an angle $\theta = 60$ mrad, first passed through an iron collimator, 6 mm wide, 3 cm high, and 1.5 m long, placed 30 m away[5]; the collimated proton beam was then momentum-analyzed by a 4-m long bending magnet (bending angle 90 mrad) and detected by a double coincidence telescope consisting of two scintillators each 1 cm wide and 2 cm high, placed 25 m away from the magnet. The resolving power $\Delta p/p$ of this arrangement was about 1% and was determined by source dimension, slit width, counter width, scattering in the air, energy spread of the circulating beam, and the Fermi motion of the nucleons in the target.

Figure 1 shows the momentum spectra observed for nine values of the circulating beam momentum. The scales given for the cross sections were deduced from another scattering measurement, performed with the external proton beam. Their absolute values must be considered only indicative, as an error even larger than two cannot be excluded at this time.

In the first seven spectra of Fig. 1, two peaks are well resolved. We call the most energetic one the elastic peak, and the second one the quasi-elastic peak. In all nine spectra a continuum is also present, the quasi-elastic continuum, extending from the largest momenta to the lowest. Eventually, this continuum merges with that due to the already well-known process of multiple production.

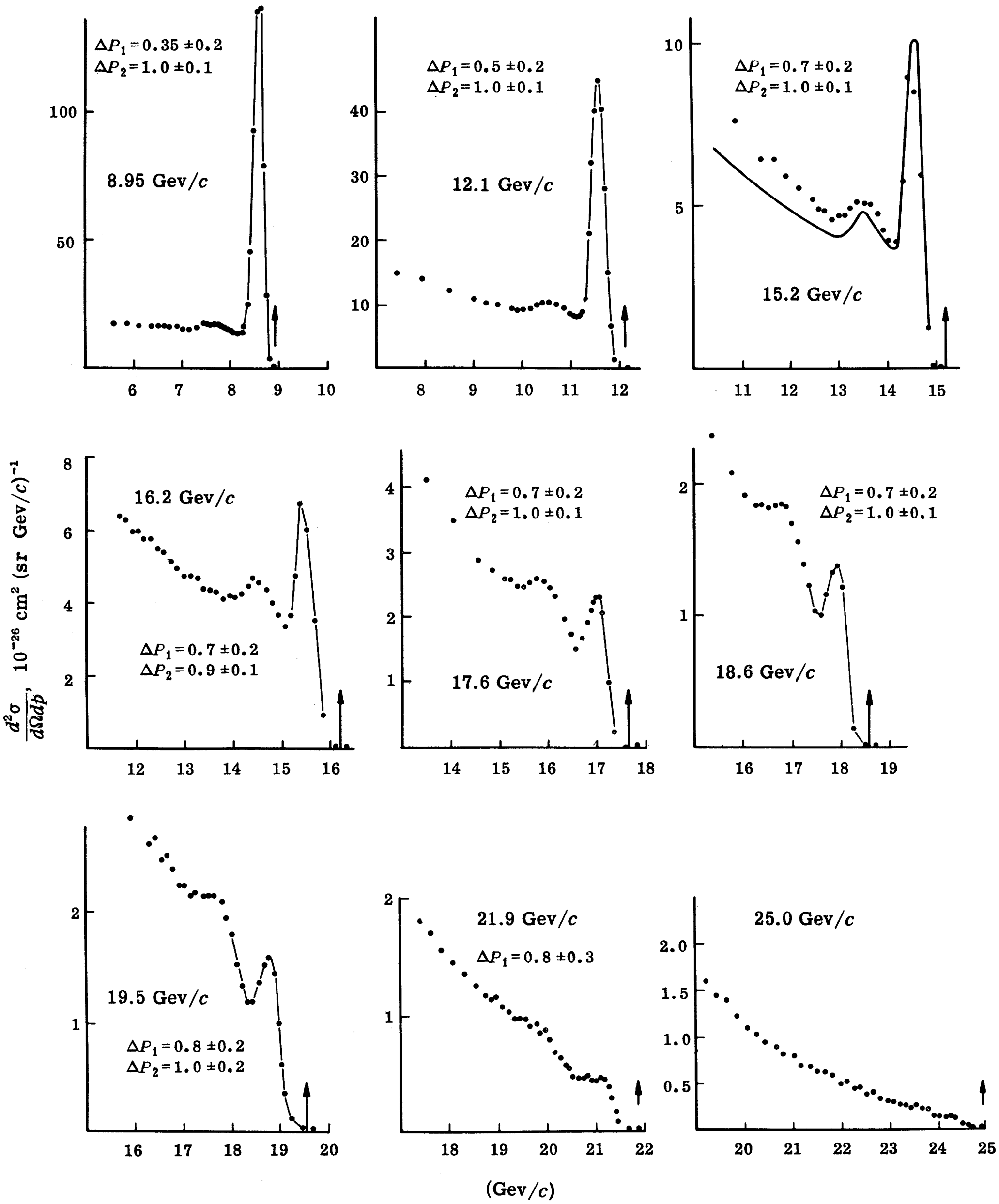

FIG. 1. Momentum spectra of the positive particles emitted at 60 mrad to the internal proton beam by a Be target. For each spectrum are given, in Gev/c, the momentum of the circulating beam (arrow), Δp_1 = momentum of circulating beam - momentum of elastic peak, Δp_2 = momentum of elastic peak - momentum of quasi-elastic peak. At 15.2 Gev/c, the line corresponds to the spectrum observed with a tantalum target, roughly normalized to that observed with the Be target. The cross sections are "per nucleon" of the Be nucleus.

We believe that the particles detected in the elastic peak, the quasi-elastic peak, and the quasi-elastic continuum are protons and that they are produced in the interaction of the primary protons with the single nucleons of the Be nuclei. Mesons can be excluded on the ground that, at 25-Gev operating energy and $\theta = 110$ mrad, the ratio mesons/protons decreases steadily for increasing energy of the secondaries and is already 1/30 at 18 Gev.[6] We have also found in another measurement at 25-Gev operating energy and for angles $\theta \leq 50$ mrad that the negative secondaries with momenta above 20 Gev/c are negligible in comparison with the positive ones. Hyperons can be ruled out because the particles we observed must have lifetimes, at rest, greater than $\sim 10^{-8}$ sec.

In order to be convinced that the quasi-elastic protons were produced in proton-nucleon collisions, a run was made, at 15.2 Gev/c, with a tantalum ($A = 181$) target. It gave exactly the same features as the Be run (see Fig. 1), thus showing, within the accuracy of the measurement, that the phenomena here discussed were not influenced by the atomic number of the target.

The elastic peak is then interpreted as due to the diffraction scattering of the protons by the nucleons. This is confirmed by the fact that experimentally the difference between the momentum of the circulating beam and that of the elastic peak, Δp_1, satisfies, within the experimental errors, the relation $\Delta p_1/mc = \frac{1}{2}\gamma^2\theta^2$ ($\gamma \gg 1$, $\theta \ll 1$) which expresses the momentum loss due to the elastic nucleon recoil. If the Fermi motion of the nucleons in the nuclei is taken into account, the disappearance of the elastic peak at 60 mrad for momenta around 20 Gev indicates a characteristic radius of interaction of about 1 fermi.

The quasi-elastic continuum could be interpreted as the result of the exchange of a virtual neutral pion as described by Salzman and Salzman[2] and by Drell.[3] The cross sections evaluated by Drell are in fair agreement with those observed. The quasi-elastic continuum is present at all momenta, thus indicating an angular distribution wider than that of the elastic scattering, also as predicted by Drell. It is worth pointing out that the cross sections for positive secondaries predicted by the statistical model, as evaluated by Hagedorn,[7] are about a factor of 10^3 smaller than those observed at 4 Gev/c below the elastic peak and even smaller at the quasi-elastic peak.

The most unexpected result is the discovery of the quasi-elastic peak. The reality of its existence is confirmed by other measurements performed at $\theta = 20$ mrad and at $\theta = 40$ mrad (Fig. 2). The experimental layouts at these two angles were similar to that described for $\theta = 60$ mrad, except that the doughnut walls were in the path of the scattered beams and corresponded to 100 and 50 g cm^{-2} of iron, respectively. Large errors are introduced into the computation of the solid angle and hence in $d\sigma/d\Omega$ as the distortions produced by the fringing fields of the accelerator are strongly momentum dependent at these angles and not yet well evaluated. Nevertheless, from Figs. 1 and 2 it is clear that the quasi-elastic peak is present *whenever* and *only when* the elastic peak is present and that the momentum difference between the two peaks, Δp_2, is, within experimental errors, constant and equal to ≈ 1 Gev/c, independent of scattering angle and proton momentum.

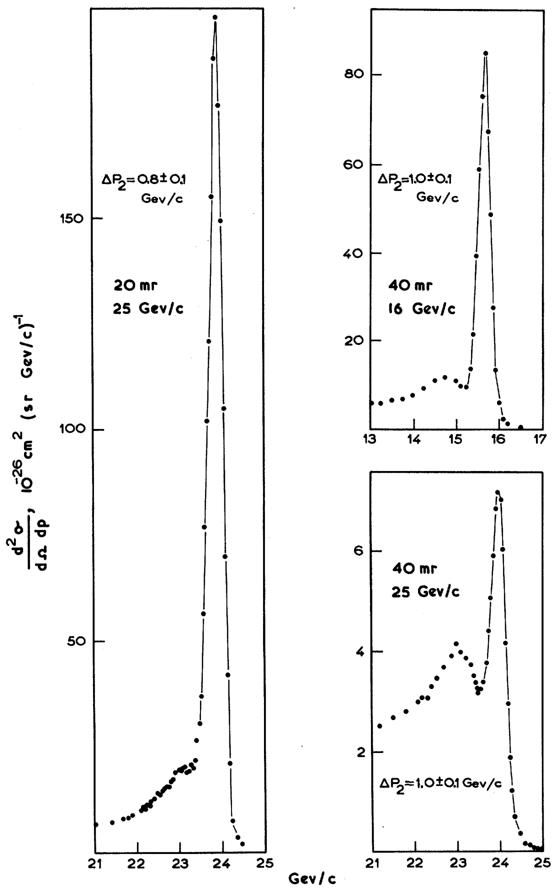

FIG. 2. Momentum spectra at 20 and 40 mrad to the circulating beam, observed with Be targets.

The correlation between the quasi-elastic peak and the elastic peak seems to rule out the possibility that the quasi-elastic peak is due to the exchange of a single π^0, enhanced by the well-known resonances observed in the pion-nucleon interaction for pion total energies around $c\Delta p_2$.

Following a suggestion by L. van Hove, the observed features could instead be explained by assuming that the quasi-elastic peak is due to the diffraction disintegration of the target nucleons induced by the ultrarelativistic protons. Repeating for the nucleon-nucleon interaction the arguments discussed by Good and Walker[8] for the nucleon-nucleus case, it is possible to predict that the diffraction dissociation of the target nucleon into a nucleon and a pion must take place, at our energies, only when ~ 1 Gev is absorbed and that it must be present, of course, only when the elastic diffraction scattering is present. Only further experiments will enable us to confirm, or not, this suggestive interpretation.

Finally, we want to point out that the existence of the quasi-elastic collisions (the quasi-elastic continuum) for ultrarelativistic protons can have interesting applications.

One concerns radiochemistry. When the quasi-elastic event takes place for the target nucleon embedded in a nucleus it is easily seen that the final momentum of the target nucleon, in the lab system, can be so small as to leave the nucleon inside its original nucleus. The exchange of a pion can then give rise to a nuclear reaction of the type $X_Z{}^A(p,p\pi^\mp)Y_{Z\pm1}{}^A$. The cross sections evaluated for this phenomenon seem to be of the right order of magnitude for explaining several reactions of this kind, as well as others of similar character, produced by ultrarelativistic protons.[9]

A second remark concerns the possibility of using quasi-elastic events for building a separator of ultrarelativistic antiprotons. Whereas it is expected that the quasi-elastic cross section of antiprotons is equal to that of the protons, the mesons should have quasi-elastic cross sections substantially smaller, being unable to exchange a single pion with a nucleon. A monochromatic secondary beam of ultrarelativistic negative particles containing antiprotons, pions, K mesons, and muons should then, when scattered by a target, give a tertiary beam of quasi-elastic particles enriched in antiprotons according to the ratio of the cross sections. Guesses about intensities and cross sections seem to indicate that such a separator could be of value for bubble chambers at momenta where most of the separators suggested so far will certainly fail. A separator of this kind would also be relatively cheap.

These measurements would have been impossible without the warm collaboration of the proton synchrotron staff. We want to thank in particular Mr. J. Gervaise, who acted as liaison man between our group and the Machine Group. We also thank Mr. C. A. Stahlbrandt for his skillful help with the electronics.

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SEARCH FOR THE ω^0 IN PHOTOPRODUCTION

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A recent investigation by Abashian, Booth, and Crowe[1] of the He^3 recoil momentum spectrum in the reaction

$$p+d\rightarrow He^3+\ldots, \tag{1}$$

has revealed, in addition to the peak associated with π^0 production and the continuum associated with double-pion production,

$$p+d\rightarrow He^3+\pi^0, \tag{2}$$

$$p+d\rightarrow He^3+\pi^++\pi^-, \tag{3}$$

$$p+d\rightarrow He^3+\pi^0+\pi^0, \tag{3'}$$

an anomalous peak which has been interpreted as being associated with a resonant state of two pions or a particle of mass 310 ± 10 Mev. In the following we shall refer to this particle or resonance (the distinction is perhaps only a matter of lifetime) as if it were a particle ω^0:

$$p+d\rightarrow He^3+\omega^0. \tag{4}$$