# Production Spectrum of Mesons in High-Energy Nucleon-Nucleon Collisions*

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In order to obtain a production spectrum of mesons in the center-of-mass system, three high-energy nuclear collisions were selected which satisfy very stringent criteria for nucleon-nucleon collisions and for which the momenta of all charged particles could be measured in the laboratory system. The results show that more than one-half of the mesons have energies less than 1 Bev in the center-of-mass system. Only a few particles emitted under very small angles in the forward and backward direction have higher energies, extending up to 10 Bev. The low-energy end of the spectrum is compared with results obtained in experiments with the Berkeley Bevatron.

THE existence of multiple meson production is now a well established experimental fact. The problem has also been approached theoretically by several authors.[1–6]

At present, one of the most important physical quantities to be compared with the theoretical predictions is the energy spectrum of the particles in the center-of-mass system. During the last few years, several attempts have been made in this direction without leading to very satisfactory results.[7–10]

In order to obtain a production spectrum of mesons, three events found in our laboratory were used which satisfy several very stringent criteria and have energies of more than $10^{12}$ ev. Commonly, high-energy collisions observed in nuclear emulsions flown by balloons at very high altitudes are explained in terms of nucleon-nucleon collisions. Unfortunately, however, most of the events observed by this method are not nucleon-nucleon collisions but nucleon-nucleus collisions, because nuclear emulsions consist mostly of heavy elements. This means that the particles produced in a primary nucleon-nucleon collision will undergo further interaction within the same nucleus which will disturb the energy and angular distribution of the primary collision. It is, therefore, a generally accepted practice in such investigations to select jets which have no heavy prongs at all or to accept only events which have one or two heavy prongs. This is the best approximation to a collision between a nucleon and a free proton or between a nucleon and only one bound nucleon at the periphery of a nucleus. But it is evident that these criteria are not completely safe, because the emission of neutrons only as a result of some excitation of a nucleus cannot be excluded entirely. One has, therefore, to apply further criteria, like symmetry, and energy and momentum balance between the forward and the backward cones in the center-of-mass systems.

Our three events seem to fulfill these conditions in the best possible way; hence, they are consistent with nucleon-nucleon collisions. A very large number of other events which do not fulfill these criteria had to be disregarded because they cannot be classified as nucleon-nucleon collisions.

The first event of type $2+15\,p$ ("$S$ star") has been described in full detail previously.[11–13] The other two events, of types $0+20\,p$ and $0+20\,n$, have been described briefly[14] and will soon be published in full detail. The first one has a primary energy close to $5\times10^{12}$ ev, the latter close to $1\times10^{12}$ ev as determined by the kinematics of the two events. The energies of all secondary particles were measured in the laboratory system using multiple scattering methods. Particles which, in the center-of-mass system, are emitted in the forward cone have rather high energies in the laboratory system. An estimate of their energy can be obtained only by relative track-to-track scattering.[11,13] In the backward cone, the energies in the laboratory system are fairly low and can be measured by single-track scattering. In all cases where particles in the forward cone produced high-energy secondary interactions, their kinematics were used as an independent estimate of the energy.

The Lorentz transformation from the laboratory system into the center-of-mass system could then be calculated for each individual track, knowing its angle and momentum and assuming a nucleon-nucleon collision. Furthermore, we assumed that all particles produced in the collision are $\pi$ mesons which must not

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be completely true. Recent observations[15] indicate very strongly that even at primary energies greater than $10^{13}$ ev, only about 20% of the particles could be different from $\pi$ mesons. The Bristol group came to similar conclusions for collisions of energies greater than $10^{12}$ ev.[16] Therefore, as a first approximation, it seems quite reasonable to assume that the particles are $\pi$ mesons. The consistency of our measurements and our assumptions could be checked by symmetry, energy and momentum balance in the center-of-mass system for each individual event. The transformation for tracks, in the backward cone, which have low energies in the laboratory system, is very sensitive to the mass of the particles. By assuming masses heavier than $\pi$ mesons, the energy and momentum balance in the center of mass would be greatly disturbed.

Our results for the three events are represented in Fig. 1. The number of $\pi$ mesons per unit interval equal to one $\pi$-meson rest mass ($m_\pi c^2$) is plotted as a function of the total energy of the created mesons in units of $m_\pi c^2$ in the center-of-mass system. The striking feature of this spectrum is that more than one-half of the mesons have energies less than 1 Bev. It can also be shown that the shape of this spectrum, at primary energies greater than $10^{12}$ ev, where the energies in the center-of-mass system available for meson production are greater than 50 Bev, is remarkably insensitive to possible uncertainties in the estimates of the primary energies. In our events, the values of $\gamma_c=1/(1-\beta_c^2)$ ($\beta_c$=velocity of the center of mass) are estimated to be correct within about 20%. The shaded area in the spectrum includes all tracks for which the scattering measurements gave definite values of momenta (error less than 50%). These errors do not influence the shape of the spectrum at its lower end, because they can cause only minor shifts for individual tracks. The existence of high-energy mesons up to 10 Bev seems to be well established. Their frequency, of course, is small and they are emitted under very small angles in the forward and backward direction in the center-of-mass system. This is in good agreement with the observed low values of the transverse momentum.[16,17] The unshaded area is due to tracks for which only a lower limit of the energy could be established by relative scattering measurements. Four out of six such tracks in the spectrum peak near 0.3 Bev belong to the event $0+20\,n$. For this event, a very detailed study of energy and momentum balance in the center-of-mass system shows that these tracks might, on the average, be shifted about 1 Bev towards higher energies, leaving the shape of the spectrum undisturbed.

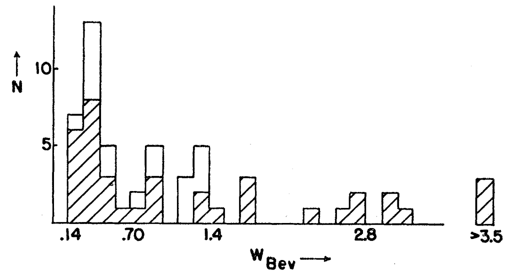


FIG. 1. Differential energy spectrum of mesons in the center-of-mass system produced in three nucleon-nucleon collisions with $E\geq 10^{12}$ ev. $N$ is the number of particles produced and $W$ is the total energy of the mesons in intervals of one $\pi$-meson rest mass.

Our production spectrum at the lower end can be compared with the $\pi$-meson spectrum of $\pi^-$-$p$ collisions at 5 Bev which were investigated in Berkeley, using a hydrogen diffusion chamber in a magnetic field,[18] and with the pion spectrum arising from antiproton annihilations as reported in nuclear emulsion by the Berkeley and Rome Groups.[19] It is remarkable to observe that these three $\pi$-meson spectra have rather similar shapes. In the two Berkeley experiments, the energy available in the center-of-mass system is about the same; i.e., 2 Bev.

It has to be explained why, at energies greater than $10^{12}$ ev, where more than 50-Bev energy is available in the center-of-mass system, most of the charged particles have either to be created directly[1,2] at these low energies, or if they are created as fast particles[4] they have to lose a considerable fraction of their energy by secondary interactions.[3,5] It might also be possible to discuss such low energy $\pi$ mesons in terms of annihilation processes of those baryon antibaryon pairs which are emitted at rather low energies.[20]

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