Energy Determination from Multiple Meson Production by 6.3-Bev Protons in Nuclear Emulsion

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864 stars produced by the 6.3-Bev proton beam of the Berkeley Bevatron were observed in nuclear emulsion. The average number of shower particles was 2.7 prongs per star. The energy of the primary particle was determined by three different methods: (*a*) the median angle method; (*b*) Castagnoli's method; (*c*) Cocconi's graphical method. It is found that the results of these three methods are in good agreement with each other and are high in each case by a factor of 2.

I. INTRODUCTION

At high energies the only available methods for finding the energy of the primary particles which produce stars in a nuclear emulsion are from the angular distribution of the shower particles which are produced in the interactions. The methods depending on angular distribution presuppose the following assumptions:

(1) All the shower particles are produced in a single nucleon-nucleon collision.
(2) Secondary interactions of the primary particles and mesons within the target nucleus are neglected.
(3) The velocity of all the particles in the center-of-mass system of the collision is the same and is equal to the velocity of the center of mass itself.

With these assumptions one can use the following methods for finding the energy per nucleon of the incoming primary particles:

(*a*) Median angle method,

$$\gamma_c = \cot\theta_{\text{med}},$$

where θ_{med} = the median angle of the shower enclosing half of all the shower particles in the laboratory system. γ_c is the energy of the primary particle in the center-of-mass system in units of its rest energy.
(*b*) Castagnoli's[1] method,

$$-\log\gamma_c = \frac{1}{n}\sum_{i=1}^{i=n} \log \tan\theta_i,$$

where θ_i is the angle which the ith shower particle makes with the direction of the primary in the laboratory system. n is the total number of shower particles produced in the interaction.
(*c*) Graphical method. We shall also make use of the graphical method, first given by Duller and Walker, of plotting $\log\{F(\theta)/[1-F(\theta)]\}$ *vs* $\log\tan\theta$ for each individual event, where $F(\theta)$ is the fraction of all particles having an angle $<\theta$ in the laboratory system, thus finding the intercept for $F(\theta)=\frac{1}{2}$ whereupon $-\log\gamma_c = \log\tan\theta_{\text{med}}$. The primary energy, γ_P, per nucleon in units of the rest energy of a nucleon in the laboratory system is then found from the relation $\gamma_P = (2\gamma_c^2 - 1)$.

Methods (*b*) and (*c*) make use of all the angles which the shower particles make with the direction of the primary, while method (*a*) uses only a part of the information contains in the angular distribution. We would like to report on an angular distribution analysis of the shower particles produced by 6.3-Bev protons, that critically tests the above methods of analysis for determining the primary energy.

2. EXPERIMENTAL DETAILS AND THE RESULTS

864 nuclear stars produced by the 6.3-Bev proton beam of the Berkeley Bevatron were observed by area scanning in 600-micron G-5 stripped emulsions. There were 2351 shower particles ($g \leqslant 1.5\, g_m$) and the average number of shower particles was 2.7 prongs per star. The number of borderline cases between gray and light tracks was very few and should not affect the average value. This average value is quite compatible with the value of 2.6 prongs per star given previously.[2] In Fig. 1 are given the frequency distributions of the number of shower particles per star for stars N_h (number of black

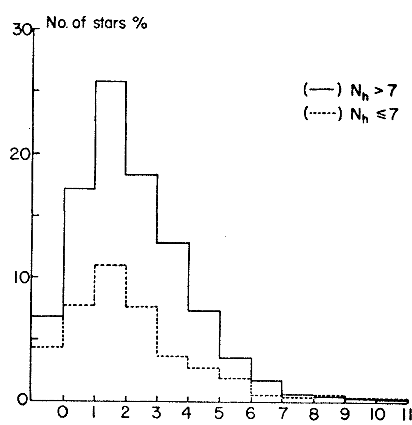

FIG. 1. Frequency distribution of the number of shower particles for stars $N_h \leqslant 7$ and $N_h > 7$. $\bar{n}_s = 2.9 \pm 0.2$ for $N_h > 7$ and $\bar{n}_s = 2.4 \pm 0.2$ for $N_h \leqslant 7$.

[1] C. Castagnoli *et al.*, Nuovo cimento **10**, 1539 (1953).

[2] Appa Rao, Daniel, and Neelakantan, Proc. Indian Acad. Sci. **43A**, 181 (1956).

TABLE I. Total everage energy value as determined by three different methods.

1	2	3	4	5	6		7	
							Average E_p by	
N_h	Type	Total no. of indep. stars	Total no. of comp. stars	Total no. of indiv. stars used for stars in col. 4	Total n_s	θ_{med} (*a*)	$\langle\theta\rangle$ (*b*)	$F(\theta)$ (*c*)
2	Comp.		1	7	17	9.5	12.1	14.0
	Ind.	1			7	13.4	10.9	11.5
3	Comp.		2	18	37	20.6±1.0	16.6±2.2	16.8±2.0
4	Comp.		4	37	88	14.8±1.0	14.2±1.0	12.3±0.8
	Ind.	3			21	23.1±2.5	15.4±2.2	14.8±1.7
5	Comp.		8	61	160	12.6±0.6	10.2±0.4	9.9±0.4
	Ind.	5			31	22.6±1.5	20.0±1.4	18.6±1.2
6	Comp.		6	58	137	23.9±1.5	16.7±0.6	18 7±1.2
	Ind.	5			36	16.8±1.8	15.4±1.4	15.4±1.4
7	Comp.		5	45	108	12.3±1.2	11.0±0.8	10.8±0.8
	Ind.	2			16	23.6±1.1	17.8±3.6	15.8±3.4
	Comp.				Average	15.6±0.9	13.5±0.8	13.8±0.9
	Ind.					19.9±1.7	15.9±2.2	15.2±1.9
8	Comp.		5	42	110	10.0±1.6	8.6±1.2	8.7±1.3
	Ind.	5			39	11.9±0.6	11.7±0.8	11.4±0.9
9	Comp.		6	46	133	10.3±0.5	8.5±0.5	8.4±0.4
	Ind.	4			32	10.7±2.4	10.2±2.2	9.4±2.4
10	Comp.		3	24	70	9.6±2.8	7.8±1.2	8.6±1.6
	Comp.				Average	10.0±1.6	8.3±1.0	8.6±1.1
	Ind.					11.3±1.5	10.9±1.5	10.4±1.6
					Total average	14.2±1.7	12.2±1.4	12.0±1.4

and gray prongs) $\leqslant 7$ and $N_h > 7$. The average number of shower particles, $\bar{n}_s$, is 2.9±0.2 and 2.4±0.2 for stars with $N_h > 7$ and $N_h \leqslant 7$, respectively. An efficiency check was made by scanning along the track and 10 cases of proton interaction with nuclei in 3.51 meters of track length were found. In neither case where any "zero prong" stars observed. The angular distributions of the shower particles for stars $N_h \leqslant 7$ and $N_h > 7$ are given in Fig. 2. From the angular distribution the values of the median angles are found to be 29° and 23° for stars with $N_h > 7$ and $N_h \leqslant 7$, respectively. We have also found that if we plot the angular distribution of shower particles in the laboratory system against the number of tracks for different ranges of multiplicity, the "width" at half maximum of the angular distribution decreases, but only very slowly as n_s, the number of shower particles in a star, increases. We have also found that the angular distribution of shower particles for stars $N_h \leqslant 7$ and $N_h > 7$ shows a broadening of the spread for $N_h > 7$, an effect which can be interpreted in terms of interactions of the shower particles with the parent nucleus.

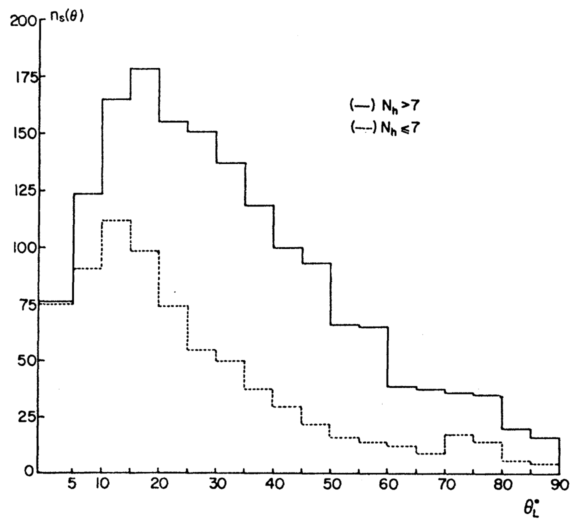

FIG. 2. Angular distribution of charged shower particles in the laboratory system for stars $N_h \leqslant 7$ and $N_h > 7$. $n_s(\theta)$ is the number of tracks with angle θ in a five-degree interval.

Figure 1 shows that only approximately 8% of the stars have more than 5 shower particles. We call these events independent stars. In order to have a sufficient number of particles for the application of the above methods (*a*), (*b*), and (*c*) we have combined stars having less than 6 particles to form "composite stars." The grouping of the stars is done according to the number of heavy and gray prongs N_h such that we have roughly the same number of shower particles in each composite star characterized by the common value of N_h. The results are shown in Table I. In the third column of this table are shown the numbers of stars which were used singly to calculate the energy value. The fourth column gives the number of the composite stars which were formed on the average from eight or nine individual stars selected at random having shower particles less than six per star and with the same N_h value. In column seven are given the energy values of the primary particle by the three methods (*a*), (*b*), and (*c*). The errors shown are estimated standard deviation. For these methods, only the mesons among the shower particles (meson plus proton) should be considered. In the composite stars the number of knock-on protons is much greater than in the single independent stars and the result is that the energy value fluctuates appreciably about the true value. Only method (*c*) helps

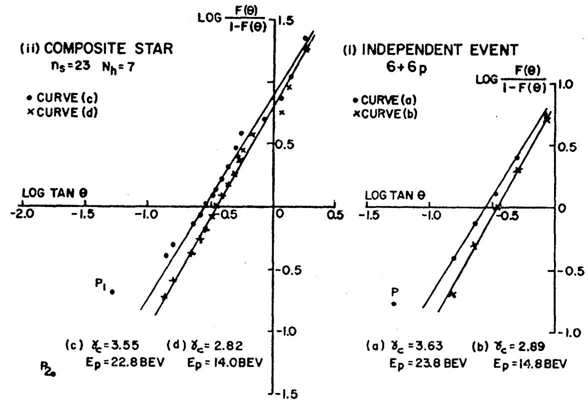

FIG. 3. Angular distribution of charged shower particles for two types of events. $F(\theta)$ is the fraction of all the particles in the laboratory system found in a cone of half opening angle θ. E_p is the energy of the primary particle in the laboratory system.

to some extent in separating the knock-on protons from the mesons among the shower particles.

In Fig. 3(i) is shown an independent event of six shower particles. Point P does not lie on curve (*a*) of slope 1.70. If we exclude this point, considering it to be a knock-on proton, the new curve (*b*) with a slope of 1.92 passes through all the five points. The value of the slope of the curve drawn for mesons with isotropic angular distribution in the c.m. system should be 2.[3] A slope value of little less than 2 slightly favors collimation in the forward direction. The energy value derived from curve (*b*) is much more reasonable than from curve (*a*) The same technique has been used for composite stars, although it is much more difficult than in a single independent star because in a composite star there are a greater number of knock-on protons. In Fig. 3(ii) is show a composite star formed from individual stars having a total number of 23 shower particles. Points P_1 (triply weighted) and P_2 (singly weighted) do not lie on a possible curve (*c*) of slope 1.68 and are considered knock-on protons as in Fig. 3(i). After neglecting these points, we get a new curve (*d*) of slope 1.90 from 19 shower particles, which has a much better fit for the plotted points than the curve (*c*). The energy values in the two cases are quite different. This technique has been used in all events to separate the most probable knock-on protons which may lie among the shower particles.

[3] G. Cocconi, Phys. Rev. **111**, 1699 (1958).

3. DISCUSSION

Table I shows that the average value of the energy of the primary particle as calculated from stars with $N_h \leqslant 7$ is higher than from stars with $N_h > 7$. The energy values calculated by methods (*b*) and (*c*), where we made use of all the angles of shower particles, are much more consistent than by method (*a*). On the whole the results of all three methods are in good agreement with one another and are consistently too high in each case by a factor of 2. The reason for this is that although we have tried to separate the protons from among the shower particles, nevertheless, because of the very low average multiplicity (2.7 per star) of shower particles, the protons among them especially in composite stars do influence the results greatly, as their velocity in the c.m. system is not equal to the velocity of the primary proton. In independent events, although most of the shower particles are mesons, they have a velocity distribution and all of the mesons produced in nuclear interactions are not of the same velocity as the center of mass itself, some of them having very low energy in the c.m. system. Also the large number of gray and black prongs in stars indicates that there may be a secondary interaction in some of the primary particles and mesons with the target nucleus. All these points are contrary to the assumptions under which the above three methods are applicable for energy determination from the angular distribution of the shower particles. We may also point out that the larger the number of individual stars contained in a composite star, the more will be the number of knock-on protons present among the shower particles and the more difficult it becomes to draw the true Cocconi's diagram. Hence, the energy values calculated will be far from the true value. In order to obtain the total average energy value between 12.0 and 12.2 Bev as shown in Table I, one has to use a multiplication factor of 1.38 for γ_c in methods (*b*) and (*c*). This multiplication factor is approximately the same as found earlier[4] by a different method, though the energy considered in that case was much higher than reported here.

4. ACKNOWLEDGMENTS

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[4] Jain, Lohrmann, and Teucher, Phys. Rev. **115**, 643 (1959).