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Analysis of multiparticle production data on proton-nucleus collisions using a new variable

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Abstract. Multiparticle production data on proton-nucleus collisions have been analyzed taking the number of 'created' charged particles instead of the observed number of shower particles as the variable. The mean normalized multiplicity, R_A, has been found to be independent of energy in the energy range (7-8000) GeV and its mass number dependence has been obtained. The modified analysis introduces some more regularities in the experimental results on p-nucleus collisions like the invariance with respect to energy of the relationship $R_A = \alpha + \beta N_h$ and the KNO-like scaling of the multiplicity distributions of the created charged particles. The functional form of the scaling function has been calculated.

Keywords. Multiparticle production; hadron-nucleus collisions; created particles, mean normalized multiplicity; target-size dependence.

1. Introduction

In recent years, it has been realized that the observed asymptotic state of hadron-nucleon collision is insufficient to provide enough insight into the production dynamics involved in these interactions and for deeper understanding of these processes interference with the evolving state before its reaching to multiparticle final state is necessary. The nuclear targets for this purpose are ideal because they provide the unique possibility of the interference through the space-time development of production process (Fishbane and Trefil 1971, 1973; Dar and Vary 1972; Subramanian 1972; Fishbane *et al* 1972, 1973; Goldhaber 1973; Gottfried 1973, 1974). This idea has resulted in the revival of interest in the hadron-nucleus interaction studies.

An important parameter widely used to study this development of production process is R_A which has often been referred to as the 'mean normalized multiplicity' and is defined as $R_A = \langle N \rangle / \langle n \rangle$ where $\langle n \rangle$ is the average multiplicity for collisions with a proton target and $\langle N \rangle$ is the corresponding quantity for a nuclear target of mass number A; the projectile and the energy being same in both the cases. The knowledge of the dependence of R_A on A and E is considered useful in distinguishing between the models of multiparticle production which may be grouped into two broad classes. Class one models (single step models) are those where the asymptotic state is assumed to reach immediately after the collision and the particles are free to interact with other nucleons of the nucleus and thereby establish an internuclear cascade. These models predict energy dependent value of R_A much higher than unity. In class two models (double step models) the asymptotic state is delayed through the formation of intermediate states that have well defined life times in their rest frames so that particles become physical well outside the nucleus. This results in suppression of multiplicities. The value of R_A is, therefore, expected to be energy independent and much smaller than that based on class one models.

In recent years the dependence of R_A on energy, E, and mass number, A, has been extensively studied experimentally (Babecki *et al* 1973, 1974; Friedlander *et al* 1974; Gurtu *et al* 1974; Jain *et al* 1974, 1975 a,b; Otterlund 1974; Calucci 1974; Babecki 1975; Tretyakova 1974; Holynski *et al* 1974; Gibbs *et al* 1974; Hebert *et al* 1975, 1977; Atanelishivily *et al* 1975; Jones *et al* 1975; Azimov *et al* 1976; Guty *et al* 1976; Florian *et al* 1976; Agarwal *et al* 1976). It has been reported that R_A increases with energy up to $E \sim 100$ GeV and thereafter it attains essentially a constant value equal to A^{α} with $\alpha = 0{\cdot}13$. This behaviour of R_A favours the single step mechanisms up to energies ~ 100 GeV and the double step mechanisms at higher energies.

The aim of the present study is to draw the attention to the fact that the relation used by different authors for estimating R_A from the experimental results is not in accordance with its definition used to predict its behaviour under different models. The predictions of the models are based on the definition of R_A as the ratio of all the final state particles produced in hadron-nucleus and hadron-nucleon collisions but what has been done is different because, generally, the ratio of only the charged showers (relative velocity $\beta \geqslant 0{\cdot}7$) of hadron-nucleus collisions and all the charged particles of hadron-nucleon collisions have been considered. Thus, two dissimilar quantities have been compared. This affects the conclusions drawn regarding the energy and mass number dependence of R_A and, therefore, the consequent deduction from it.

2. Estimation of R_A

Although, it is very difficult to have an exact knowledge of all the final state particles of hadron-nucleon and hadron-nucleus collisions and consequently of R_A, we here suggest some ways to estimate R_A so that its comparison with different models may become meaningful.

2.1. *Estimation of R_A by considering all the final state particles*

The best but the most difficult way would be to use the total number of final state particles produced in hadron-nucleon and hadron-nucleus collisions to estimate the value of R_A. In case of *pp* collisions the average charged multiplicity $\langle n_{\rm ch}\rangle$, represents the average number of total charged particles present in the final channel in which the two charges of initial channel are also included. Therefore, subtracting 2 from $\langle n_{\rm ch}\rangle$ gives only the 'created charges' (essentially pions) of the final channel. Using the observation of charge symmetry (e.g. Daniel *et al* 1973; Boggild *et al* 1971 and Jones *et al* 1975 report that $\frac{1}{2}\langle n_\pi \pm\rangle = \langle n_\pi 0\rangle$) we may take that 3/2 $\langle n_\pi \pm\rangle$ particles are created in a *pp* collision and thus the average number of total particles (charged and neutral both) in the final state may be given as;

$$\langle n\rangle = 3/2\ (\langle n_{\rm ch}\rangle - 2) + 2. \tag{1}$$

Similarly, subtracting 1 from $\langle N_s \rangle$ which corresponds to the proton in the incident channel, where $\langle N_s \rangle$ is the average number of shower particles observed in p-nucleus collisions, one gets the number of charged particles 'created' in p-nucleus collisions. These particles are characterised by the relative velocity $\beta \geqslant 0{\cdot}7$. However, a very small fraction of the produced particles appears as grey tracks (slow pions), i.e., with $\beta < 0{\cdot}7$. The number of such pions is $\sim 8\%$ of the total number of grey tracks at lower energies (Gottfried 1973 and Khan *et al* 1977). At 24 GeV, Khan *et al* report the frequency of slow pions, appearing as grey tracks to be $\sim 0{\cdot}33$. For proper analysis this fraction of slow pions must also be taken into account while estimating the number of created particles. However, since this fraction is small enough to give rise to any significant effect on the results, we neglect it at present. Therefore, $\langle N_s \rangle - 1$ may be taken to represent almost all the created charged particles. Thus, the average number of total created particles may be given as:

$$\langle N_{s\pm 0} \rangle = 3/2 \quad (\langle N_s \rangle - 1). \tag{2}$$

Now adding 1 to $\langle N_{s\pm 0} \rangle$ to account for the incident proton, which must appear in the final state (as a neutron or proton), and the average number of nucleons, $\langle \nu \rangle$, encountered with the incident particle in its traversal through the nucleus, we get the average value of the total number of the particles in the final state given as;

$$\langle N \rangle = 3/2 \quad (\langle N_s \rangle - 1) + \langle \nu \rangle + 1. \tag{3}$$

Thus the value of R_A may be given as;

$$R_A = \frac{\langle N \rangle}{\langle n \rangle} = \frac{\text{Total number of particles produced in } p\text{-nucleus collision}}{\text{Total number of particles produced in } pp \text{ collision at the same energy}}$$

$$= \frac{1{\cdot}5\,(\langle N_s \rangle - 1) + \langle \nu \rangle + 1}{1{\cdot}5\,(\langle n_{\mathrm{ch}} \rangle - 2) + 2} = A^{\alpha}. \tag{4}$$

The experimental data available for the average number of shower particles, $\langle N_s \rangle$, observed in p-nucleus collisions are mainly those using the nuclei of the nuclear emulsions as the targets. The nuclear emulsions essentially compose of three groups of elements-H; CNO; and AgBr. Approximately 71% of the interactions occur with heavy nuclei AgBr ($\langle A \rangle = 94$), 25% with light nuclei CNO ($\langle A \rangle = 14$) and only 4% with hydrogen. Gurtu *et al* (1974) have compiled data on the average number of shower particles, $\langle N_s \rangle$, observed in proton interactions with emulsion nuclei at different energies (7 GeV to 8000 GeV) and have given the best fitted values for $\langle n_{\mathrm{ch}} \rangle$ at the corresponding energies. More data on proton interactions with emulsion nuclei are available but mostly with incident particles having energies ~ 200 GeV and the reported values of $\langle N_s \rangle$ are very close to those given by Gurtu *et al* at the same energy. We, therefore, use the experimental results compiled by Gurtu *et al* together with the results reported by Jain *et al* (1975) at 300 GeV for estimating the value of R_A using relation (4). We use the theoretically calculated value of $\langle \nu \rangle$ for emulsion nuclei because there is no way to know this number exactly from

Table 1. Values of R_{em} at different energies.

Energy in GeV	$\langle n_{ch} \rangle$	$\langle N_s \rangle$	$R_{em} = \frac{\langle N_{ch} \rangle cr}{\langle n_{ch} \rangle cr}$ (*)		$R_{em} = \frac{\langle N \rangle}{\langle n \rangle}$ (**)	
7·1	2·9±0·03	2·80±0·04	1·91±0·03	1·82±0·03	2·02±0·03	1·98±0·02
		2·62±0·05	1·72±0·04		1·94±0·03	
9·9	3·24±0·03	3·2 ±0·05	1·77±0·06		1·94±0·08	
20·5	4·10±0·04	5·29±0·13	2·04±0·05		2·07±0·04	
23·4	4·22±0·04	5·61±0·11	2·08±0·05		2·09±0·04	
27·0	4·41±0·04	6·23±0·2	2·17±0·07		2·15±0·06	
27·9	4·46±0·04	6·6 ±0·1	2·28±0·04		2·21±0·04	
67·9	5·89±0·07	9·57±0·23	2·2 ±0·06	2·22±0·04	2·18±0·05	2·20±0·04
		9·73±0·23	2·24±0·06		2·21±0·05	
200	7·64±0·17	13·04±0·4	2·14±0·08	2·14±0·04	2·13±0·08	2·14±0·04
		13·08±0·3	2·14±0·07		2·13±0·07	
		13·31±0·3	2·18±0·07		2·17±0·07	
		12·9 ±0·4	2·11±0·08		2·11±0·08	
300	8·86±0·16†	16·0 ±1·5†	2·19±0·21		2·17±0·18	
1000	10·6 ±0·6	19·2 ±1·9	2·12±0·24		2·11±0·23	
3000	12·6 ±0·7	21·7 ±1·6	1·95±0·18		1·97±0·18	
8000	14·4 ±0·8	23·3 ±2·0	1·80±0·18		1·83±0·18	

* $\langle R_{em} \rangle$ = 2·06 ±0·03, a = 0·181 ±0·003 ** $\langle R_{em} \rangle$ = 2·08 ±0·03, a = 0·183±0·003

† Jain *et al* (1975a)

experiments. No clear-cut separation is possible between the directly hit target nucleons and the nucleons coming out of the nucleus through the indirect push in a secondary collision and thus it is difficult to ascertain the fraction of N_g (grey tracks, $0·3 \leqslant \beta < 0·7$) or N_h (heavy tracks, $\beta < 0·7$) which represents the directly hit nucleons. We have thus used $\langle \nu \rangle_{em} = 3·2$ as evaluated by Gottfried (1973). The values of R_{em} estimated by using relation (4) have been given in table 1. It may be noticed that R_{em} remains practically constant in the entire energy range considered. The average value of R_{em} is;

$$\langle R_{em} \rangle = 2·08 \pm 0·03$$

Putting $R_{em} = A^a$, gives;

$$a = 0·183 \pm 0·003$$

2.2. *Estimation of R_A by applying β cut*

Another approach for estimating R_A is to impose a strict β cut to the final states of both the hadron-nucleon and hadron-nucleus collisions and compare the final states of different β intervals. An analysis along this line has been performed by Holynski *et al* (1974) at 200 GeV where they have compared particles in different rapidity intervals. However, sufficient amount of data in the entire energy range are needed to draw any conclusion.

2.3. *Estimation of R_A by considering only the created charged particles*

Estimation of R_A by considering all the particles produced in p-nucleus and pp collisions is in exact accordance with its definition used in predicting its behaviour on the basis of different models. What one measures experimentally is not the total number of particles produced but only the number of charged particles and as we have seen in § 2.1 that the estimation of the total number of produced particles from the experimental information involves various assumptions. However, we feel that we can get rid of these difficulties without losing the spirit of the definition of R_A if we consider the number of 'created' charged particles for estimating R_A. To estimate the number of created charged particles, the initial channel charges are excluded from the number of charged particles observed both in pp and p-nucleus collisions. In case of pp collision, two charged particles are present in the initial channel which should also appear in the final channel where the total charged particles observed are $\langle n_{ch} \rangle$. Subtracting 2 from $\langle n_{ch} \rangle$ should, therefore, give the average number of created charged particles in pp collisions, i.e., $\langle n_{ch} \rangle_{cr} = \langle n_{ch} \rangle - 2$ (Hwa 1972; Josip Soln 1976; George and Snider 1976 and Amaglobeli *et al* 1976, 1977). In the case of p-nucleus collisions the target nucleons go with energies corresponding to grey tracks and therefore, if we subtract just 1, the charge corresponding to the incident proton, from the observed $\langle N_s \rangle$ we get the number of created charged particles in p-nucleus collisions, i.e., $\langle N_s \rangle - 1 = \langle N_{ch} \rangle_{cr}$. Thus we can write;

$$R_A = \frac{\langle N_{ch} \rangle_{cr}}{\langle n_{ch} \rangle_{cr}} = \frac{\text{Number of charged particles created in } p\text{-nucleus collision}}{\text{Number of such particles created in } pp \text{ collision at the same energy}}$$

$$= \frac{\langle N_s \rangle_{-1}}{\langle n_{ch} \rangle_{-2}} = A^{\alpha}.$$

The values of R_{em} so obtained at different energies of the incident protons are given in table 1 and plotted in figure 1a. Again it may be noticed that R_{em} remains practically constant in the entire energy range. The average value of R_{em} and the corresponding value of α are;

$$\langle R_{em} \rangle = 2{\cdot}06 \pm 0{\cdot}03; \ \alpha = 0{\cdot}181 \pm 0{\cdot}003.$$

It is worth mentioning that these values of $\langle R_{em} \rangle$ and α are in excellent agreement with those obtained in § 2.1 and thus consideration of only created charged particles for estimation of R_A seems to be as good as the consideration of all the particles in the final state.

In the nuclear emulsions the interactions occur with nuclei of very varying mass numbers viz., $H(A = 1)$, CNO ($\langle A \rangle = 14$) and AgBr ($\langle A \rangle = 94$). It is, therefore, better if the interactions with these groups of nuclei be analysed separately. However, it is not possible to make an unambiguous separation of the interactions with any one group of nuclei. Kohli (1975) has, however, estimated the values of $\langle N_s \rangle$ for interactions with nuclei of CNO and AgBr groups at different energies. These values are given in table 2 and have been used to estimate the values of R_{CNO}

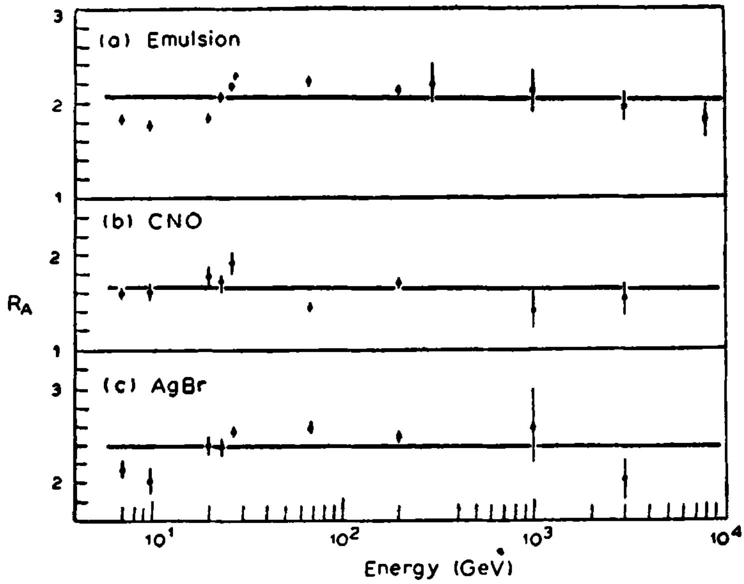

Figure 1. Variation of R_A with energy.

Table 2. Values of R_{CNO} and R_{AgBr} at different energies.

Energy in GeV	$\langle N_s \rangle$CNO	RCNO $= \frac{\langle N_{ch} \rangle cr\ (CNO)}{\langle n_{ch} \rangle cr}$		$\langle N_s \rangle$AgBr	RAgBr $= \frac{\langle N_{ch} \rangle cr\ (AgBr)}{\langle n_{ch} \rangle cr}$	
7·1	2·51 ± 0.10	1·61 ± 0·07		3·0 ± 0·1	2·13 ± 0·08	
9·9	3·0 ± 0·2	1·61 ± 0·11		3·5 ± 0·3	2·02 ± 0·17	
20·5	4·71 ± 0·34	1·77 ± 0·13		5·99 ± 0·31	2·28 ± 0·13	
23·4	4·78 ± 0·3	1·7 ± 0·11		6·26 ± 0·25	2·37 ± 0·10	
27·0	5·6 ± 0·4	1·91 ± 0·14		7·1 ± 0·25	2·53 ± 0·09	
67·9	7·4 ± 0·3	1·65 ± 0·07		11·0 ± 0·3	2·57 ± 0·08	
200	10·5 ± 0·5	1·68 ± 0·09	1·70 ± 0·06	15·2 ± 0·6	2·52 ± 0.11	2·48 + 0·07
	10·7 ± 0·5	1·72 ± 0·09		14·7 ± 0·5	2·43 ± 0·10	
1000	13·1 ± 1·8	1·40 ± 0·21		23·1 ± 3·6	2·57 ± 0·43	
3000	17·2 ± 2·0	1·53 ± 0·2		26·8 ± 2·0	2·43 ± 0·23	
	$\langle R_{CNO} \rangle$ = 1·66 ± 0·04			$\langle R_{AgBr} \rangle$ = 2·39 ± 0·06		
	a = 0·19 ± 0·01			a = 0·192 ± 0·005		

and R_{AgBr}. It may again be noted from table 2 and figure 1b and 1c that both R_{CNO} and R_{AgBr} are practically energy-independent. The average values of R_{CNO} and R_{AgBr} and the corresponding values of a are found to be;

$$\langle R_{CNO} \rangle = 1{\cdot}66 \pm 0{\cdot}04 \quad a = 0{\cdot}19 \pm 0{\cdot}01,$$

$$\langle R_{AgBr} \rangle = 2{\cdot}39 \pm 0{\cdot}06 \quad a = 0{\cdot}192 \pm 0{\cdot}005.$$

The anaysis, therefore, leads to an energy independent value of R_A given by $R_A = A^{0{\cdot}19 \pm 0{\cdot}01}$.

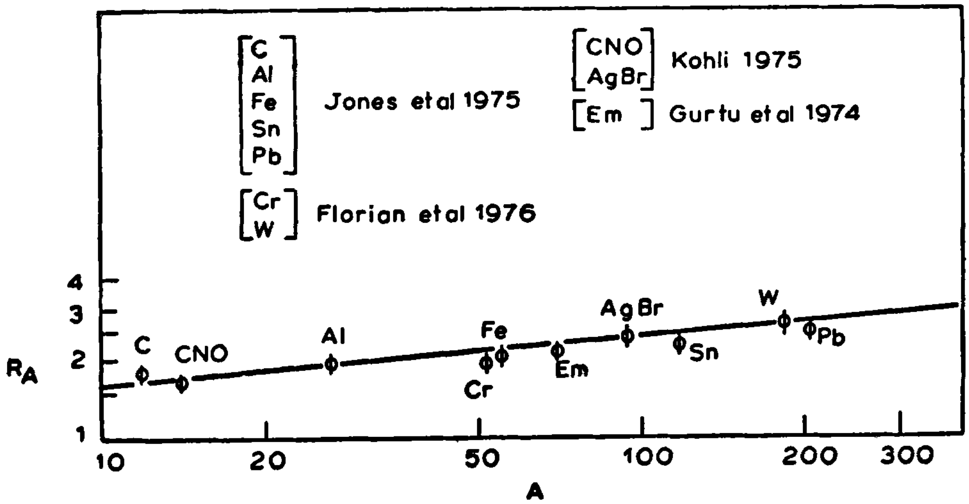

Figure 2. Variation of R_A with mass number.

The result obtained above is based on the analysis of the emulsion data and the composite nature of emulsion creates ambiguities in such an analysis. Therefore, to check the reliability of our analysis we also give an analysis of the data available for interactions with pure targets in a limited energy range reported by Jones *et al* (1975) and Florian *et al* (1976). A plot of R_A vs A on a logarithmic scale gives a straight line (figure 2) with slope $\alpha = 0{\cdot}19$ which is a best fit to the data points. It may be seen from figure 2 that the points for emulsion, CNO and AgBr also follow the same straight line.

3. R_A as a function of N_h

We shall now see that taking the number of created charged particles as the parameter in the analysis instead of $\langle N_s \rangle$ and $\langle n_{ch} \rangle$, introduces certain other regularities in the data on hadronic interactions and this in turn may lead to a better understanding of the interaction process. The variation of R_A with N_h has been studied by several workers (Babecki 1974; Otterlund 1974; Jain *et al* 1975 and Florian *et al* 1976) and a relationship of the type $R_A = \alpha + \beta N_h$ has been found to exist. The value of α has been found to remain practically constant over the entire energy range whereas β increases with energy and attains essentially a constant value $\sim 0{\cdot}1$ at energies ~ 70 GeV (Babecki 1974). However, with our modified calculations for R_A we find that both α and β become energy independent. A best fit to the plot of R_A vs N_h gives $\alpha = 1{\cdot}08$ and $\beta = 0{\cdot}13$ for the data available in the entire energy range (figure 3). Thus, the method used here leads to a kind of scaling between R_A and N_h.

4. Scaling in multiplicity distribution

The analysis of the data in terms of the number of created charged particles shows a KNO-like scaling in case of p-nucleus collisions as well down to quite low energies.

A plot between $Z' = N_{ch\,(cr)} / \langle N_{ch} \rangle_{cr}$ and $\psi\,(Z') = \langle N_{ch} \rangle_{cr}\; PN_{ch\,(cr)}$, where $PN_{ch\,(cr)}$ is the probability that the number of particles created in *p-nucleus* collisions is $N_{ch\,(cr)}$, has been given in figure 4. The data points given in the figure correspond to the interactions of protons with emulsion nuclei at energies from 22 to 300 GeV. The scaling function given by;

$$\psi\,(Z') = AZ' \exp\,(-aZ')$$

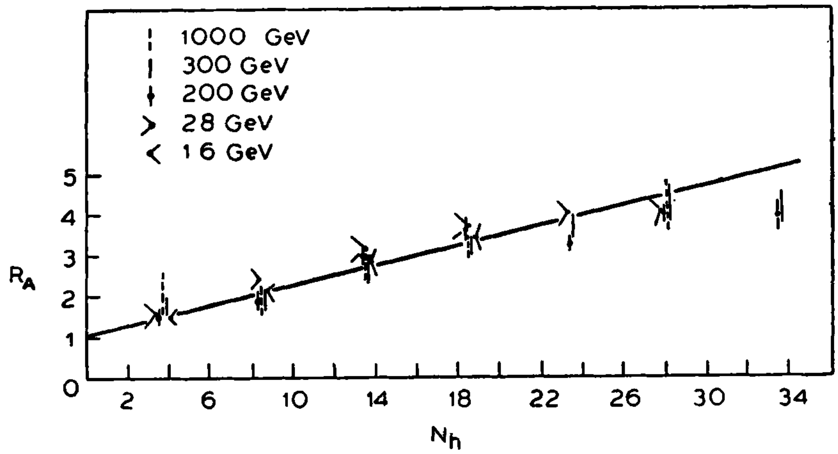

Figure 3. Variation of R_A with N_h. Data have been taken from Jain *et al* 1974. The points are at the same N_h i.e. at 3·7, 8·5, 13·5, 18·5, 23·5, 28 and 33·5. For the sake of clarity the points are slightly separated.

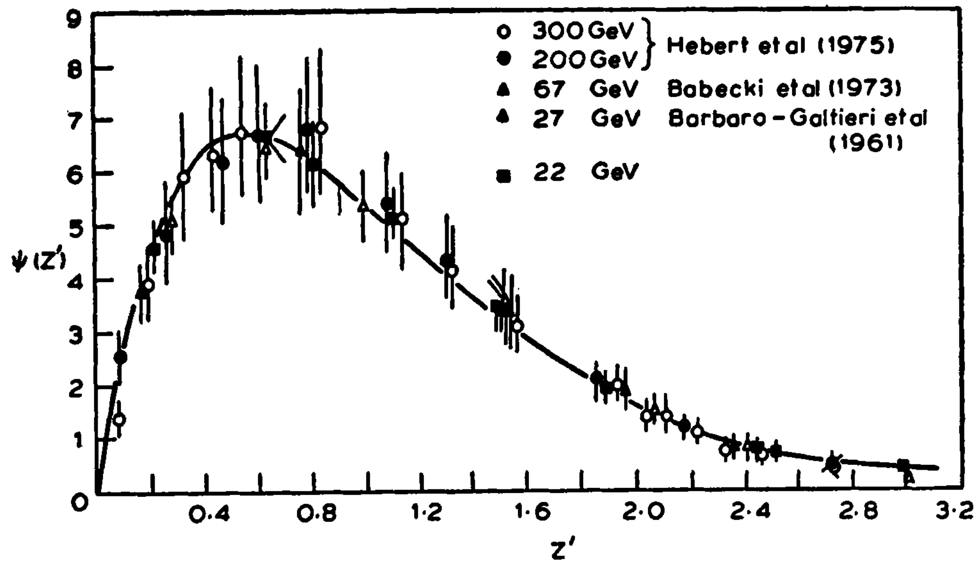

Figure 4. Scaled multiplicity distribution of charged particles created in collisions of protons with emulsion nuclei. Data have been taken from the references given in the figure. Solid line corresponds to the fitted scaling function $(Z') = 3{\cdot}3\;Z' \exp\,(-1{\cdot}83\,Z')$ where $Z' = N_{ch(cr)}/\langle N_{ch}\rangle_{cr}$. For 22 Gev, the reference is H Winzeler (1965).

with $A=3{\cdot}3$ and $\alpha=1{\cdot}83$ is found to give the best fit to the data. The overall χ^2/D.F. for all the data points is 0·54 excluding one point for $Z'>3$ at 27 GeV. Martin *et al* (1975) have also plotted $\psi(Z)$ vs Z where $Z=N_s/\langle N_s\rangle$ and have found that the scaling function,

$$\psi(Z) = (AZ + BZ^3 + CZ^5 + DZ^7)\exp(-EZ),$$

represents the data points with $\chi^2/\text{D.F.} = 0{\cdot}79$. We wish to point out that the analysis of the data in terms of created particles not only simplifies the form of the scaling function considerably but also that data covering wider energy range have been scaled with smaller value of χ^2/D.F. Further we feel that the data at much lower energies may be scaled by the same function if one could add the contribution of the slow pions produced to the number of created particles. It is worthwhile mentioning here that recently Amaglobeli *et al* (1977) have shown that analytic formula for the universal KNO-scaling function becomes very simple when the distribution with respect to multiplicity of 'truly produced' total particles is considered in hadron-nucleon collisions.

5. Conclusions

On the basis of the above analysis we arrive at the following conclusions;

(i) The number of created charged particles is a more suitable variable than $\langle N_s\rangle$ or $\langle n_{ch}\rangle$ for analysing the p-nucleus and pp data on multiparticle production.

(ii) The 'mean normalized multiplicity' R_A varies with mass number as $A^{0{\cdot}19\pm0{\cdot}01}$ and it does not depend on the energy of the incident particle.

(iii) The energy independent and only weakly A dependent value of R_A suggests that the multiparticle production occurs through double step mechanism.

(iv) The relationship $R_A=\alpha+\beta N_h$ with $\alpha=1{\cdot}08$ and $\beta=0{\cdot}13$ is invariant with respect to energy of the incident particle.

(v) A KNO-like scaling exists for multiplicity distribution of created charged particles in p-nucleus collisions in the entire energy range.

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