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Determination of the number of interacting nucleons in nitrogen–emulsion nucleus collisions

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Abstract. An experimental study has been made of the interaction of nitrogen nuclei in nuclear emulsions. Particular attention has been paid to the determination of the number of incident nucleons which participate in the interaction. It is found that on average 75% of the nucleons emerging as free particles have interacted and produced pions. This number is close to what would be expected on the assumption that the incident nucleons in the nitrogen nucleus behave independently.

The relevance of the measurements to the important case of extensive air showers initiated by heavy nuclei is considered and it is shown that the commonly used superposition model is sufficiently accurate for many applications.

1. Introduction

One of the basic problems in the investigation of super-high-energy cosmic rays is their mass composition. These cosmic rays are investigated by way of the observation of extensive air showers and it is important to know how the showers initiated by complex nuclei compare with those initiated by protons. A natural assumption to make, in first approximation, is that the nucleons from the incoming nuclei interact independently of one another and on the basis of this assumption the so called 'superposition model' has been developed and widely applied. The essence of the model is the assumption that a shower initiated by a nucleus with mass A and energy E can be taken as the sum of A showers initiated by protons with energy E/A. It is considered that such a model should be a rather good approximation in many applications as most of the energy of the incoming nucleus is released in the interactions of single nucleons.

Recently some attempts have been made to develop more sophisticated methods based on the so called fragmentation probabilities experimentally obtained for low-energy primary cosmic rays, the term fragmentation probability meaning the ratio of the number of secondary nuclei of a given group (α particles, light, medium, heavy nuclei, etc) to the number of interactions of the primary nucleus under consideration. Such treatments have been carried out by Dixon *et al* (1974) and Kalmykov and Kulikov (1974), the former taking fragmentation probabilities from the work of Waddington and Freier (1973); similar values were taken by Kalmykov and Kulikov.

2. Critical analysis of the previous work

It should be pointed out that the fragmentation probabilities allow us only to evaluate the number of nucleons (or more accurately speaking, protons since the mean charge of the emergent nucleus is measured) which remain on average bound after the collision of a given type of nucleus. By subtraction we can also get the number of released nucleons but it still remains an open question as to how many of these nucleons, on average, actually take part in the interaction (by producing pions, etc) and how many of them were simply released in the fragmentation process. This ratio is very important as it determines how quickly the showers initiated by heavy nuclei develop.

For the model in which the incoming nucleons interact independently the average number of interacting nucleons should be given by the expression:

$$N = A\lambda_A/\lambda_p$$

where λ_A is the experimental mean free path for the primary nucleus with mass A and λ_p is the proton mean free path, both for the same target nuclei. Taking $A = 14$ (medium nuclei) and corresponding values of λ_p and λ_{14} we obtain $N = 5{\cdot}4$ for air and 6·5 for nuclear emulsion as target materials.

These figures can be compared with the values adopted by the authors mentioned above (who calculated for target air nuclei). Kalmykov and Kulikov took $N = 2$ (for all medium nuclei) and in the work of Dixon *et al*, N was taken on average to be a quarter of the number of the released nucleons; in the case of $A = 14$ this corresponds to $N = 1{\cdot}85$ (the fraction of nucleons released was taken to be 0·53 following Waddington 1973, private communication). In very recent calculations by Elbert *et al* (1974) it was assumed that half of the released nucleons interact in a given collision, giving a value of $N = 3{\cdot}7$, considerably closer to the $N = 5{\cdot}4$ derived from the simple expression.

Bearing in mind the comparatively small values of N adopted by Dixon *et al* and by Kalmykov and Kulikov, it is not surprising that their calculations indicate that the showers develop more slowly than predicted by the superposition model.

3. Experimental determination of the number of interacting nucleons

The number of nucleons actually interacting can be evaluated in two ways. The first is to take the average multiplicity of the charged secondaries and to divide by the multiplicity observed in nucleon collisions (allowing for emergent protons). The second method is based on counting the number of secondary singly charged relativistic particles emitted at very small angles; these particles are obviously protons merely shaken free by the fragmentation process. Protons which have interacted or secondary particles produced in the interaction would be deviated through angles bigger by about two orders of magnitude (the mean transverse momentum for fragmentation corresponds to an energy of a few MeV whereas that for production is several hundred MeV). Assuming symmetry the total number of nucleons which are released and do not interact can be obtained. The second method is more straightforward because in the first some overlap of the meson clouds from the individual interactions is expected and, moreover, in the case of interactions with emulsion nuclei the average mass of the target nucleus decreases as the mass of the incoming particle increases because collisions with lighter nuclei become more probable. In the second method it is found experimentally that the distinction between the two types of secondary tracks is virtually unique. The first method has value, however, as an approximate check on the results.

In the present work observations were made on 90 interactions of nitrogen nuclei in the ICEF emulsion stack. The interactions were selected from a sample of several hundred due to various nuclei. A detailed description of the scanning procedure and the results obtained is given elsewhere (Sroka *et al* 1964). The results for the 90 interactions are summarized in table 1. The interactions with $N_H \leqslant 8$ are given separately as they give a better representation for the case of air.

Table 1. Basic data from the interaction measurements. I is the number of interactions, P the total number of emitted protons bound in nuclear fragments, F the number of protons emitted in the very narrow cone, N_h the number of black and grey prongs, and n_s the multiplicity of charged secondaries.

	I	P	F	$P+F$	$\langle n_s \rangle$
All	90	198	79	277	15·6
$N_h \leqslant 8$	61	170	55	225	10·4

From table 1 it can be seen that the fraction of charge which remains bound amounts to 0·315 for all interactions and 0·40 for interactions with $N_H \leqslant 8$. The corresponding values obtained by Waddington (1973, private communication) are 0·38 and 0·47. The small differences can be understood in view of the fact that Sroka *et al* did not make a special effort to find the interactions with small energy transfer, that is those where the charge of the outgoing fragment is of the same order as the charge of the primary particle. The closeness of the two sets of results is heartening and again focuses on the fact that the difference in treatments of interactions of heavy nuclei relates to the basic problem of what fraction of released nucleons have actually undergone interaction and produced pions. Assuming that the values given by Waddington are accurate a correction for the bias can easily be introduced.

The values obtained directly for the number of protons which did not interact amount to 3·1 for emulsion and to 3·7 for the air-like condition ($N_H \leqslant 8$). The values obtained after the corrections have been made are:

$$N_p = 3{\cdot}3 \pm 0{\cdot}4 \qquad \text{for emulsion}$$

$$N_p = 4{\cdot}0 \pm 0{\cdot}5 \qquad \text{for 'air'.}$$

The corresponding values for the average numbers of interacting protons are the number of protons in the nitrogen nucleus (7) minus N_p, and the total number of interacting nucleons (n and p) is thus:

$$N = 7{\cdot}4 \pm 0{\cdot}8 \qquad \text{for emulsion}$$

$$N = 6{\cdot}0 \pm 1{\cdot}0 \qquad \text{for 'air'.}$$

It should be noted that these values are slightly higher than those expected on the assumption of independent interactions (6·5 and 5·4, see § 1), but they differ only by about a standard deviation.

An approximate estimate of the number of interacting nucleons on the basis of the multiplicity of the secondaries gives values consistent with those referred to above. Indeed, the average value of the charged particle multiplicity in nucleon–nucleon collisions at 9 GeV (that is about the average energy per nucleon of the interactions considered) amounts to about 2 (Powell *et al* 1959) so that, using the values of $\langle n_s \rangle$ in table 1, the estimated number of interacting nucleons is about 7–8 for the case of emulsion and about 5 for interactions with $N_H < 8$ (the charged secondaries contain roughly the same relative numbers of pions and protons in the two cases). Thus the consistency is preserved.

At this stage it may be useful to give the results of calculations which have been made for a variety of incident nuclei. The expected values of the average fraction of interacting nucleons among those released, under the assumption of independent interactions are given in table 2. The interaction mean free paths were taken from the work of Powell *et al* (1959) and data concerning the fraction of nucleons bound after collision have again come from Waddington (1973); proton–neutron symmetry was assumed as usual.

Table 2. Average fractions of interacting nucleons amonst those released by the collision of nuclei of mass *A* with emulsion and air nuclei.

Target \ *A*	9	14	28	56
Emulsion	0·81	0·75	0·72	0·56
Air	0·74	0·72	0·65	0·57

4. Conclusions

The present measurements indicate that the average number of nucleons interacting in collisions of nitrogen nuclei in nuclear emulsions is approximately equal to 0·75 of the number of nucleons released and is thus roughly consistent with the assumption of independent interactions of the nucleons contained within the incoming nuclei. The situation for air nuclei will be similar, for example in the case of primary medium nuclei the average number of nucleons interacting should also be about 0·75 of those released. It should be noted that the picture of independent interactions gives a smaller fraction for primaries of higher mass. In the important case of primary iron nuclei it amounts to about 0·6.

Turning to the case of heavy primary cosmic ray nuclei incident on the atmosphere the results indicate that the average shower development curve of extensive air showers calculated assuming the superposition model is very nearly correct and that those fragmentation models which give much slower shower development are unrealistic. It should, however, be stressed that to be quite accurate in problems concerning extensive air shower development specific details of fragmentation should be considered, with, of course, the correct interaction probabilities.

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