A MODEL FOR HIGH-ENERGY NUCLEON-NUCLEUS COLLISIONS

J. WERLE
INSTITUTE FOR NUCLEAR RESEARCH, WARSAW,
POLAND

1. EXPERIMENTAL FACTS IN VERY HIGH ENERGY NUCLEON-NUCLEUS COLLISIONS

I would like to tell you briefly about some interesting experimental facts observed in very high energy nucleon-nucleus collisions. Then, I want to present you some single theoretical model aiming at a plausible explanation of the mentioned experimental data. By very high energy I mean the region extending from highest accelerator energies of ~ 10 GeV to the not too rare cosmic ray energy of, say, ~10^5 GeV. A typical high energy nucleon-nucleus collision can be distinguished from more elementary nucleon-nucleon or pion nucleon collisions by the presence of a number of black tracks of non-relativistic particles. What the emulsion people actually see is drawn schematically on Fig. 1.

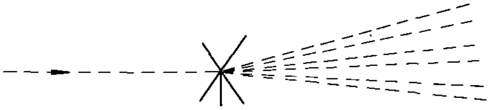

Fig. 1

Typical high energy nucleon-nucleus collision

The thick black lines refer to non-relativistic particles, the dotted lines refer to relativistic particles. At high energies of the incident particle the relativistic secondaries are emitted in a rather narrow cone whereas the non-relativistic ones are distributed almost isotropically. (Throughout this paper, I am always speaking of the situation in the laboratory system). Major part of non-relativistic particles forming black tracks consists of nucleons whereas the relativistic particles are mainly mesons. However, the experimentalists have found also heavier fragments of nuclear matter among the particles responsible for black tracks. Some number of light nuclei d, t, He, Li, Be, etc. could be identified. There is no evidence for the existence of such heavy fragments among the relativistic particles. These striking differences between the structures of relativistic and the non-relativistic parts of secondaries emitted in the same collision imply completely different mechanisms for these two phenomena.

In fact one can explain these differences by assuming two distinct stages of the very high energy nucleon-nucleus collision. The first stage, which may be called "knock off", consists of a single or a few elementary collisions between the incident nucleon and those nucleons of the nucleus which just happen to stand in its way. Some secondary pion-nucleon collisions may be also responsible for the structure of the relativistic cone. It seems that in many cases the properties of the narrow jets of relativistic particles emerging from high energy nucleon-nucleus collisions are very similar to those emitted in nucleon-nucleon collisions. I shall not speak of the properties of relativistic particles since this has already been done in some detail by Prof. Hayakawa. I will be mainly concerned with the struck nucleus or rather with what remained of it after knocking off the relativistic jets.

Here, the situation can depend very much on the energy of the incident nucleon, size of the struck nucleus, impact parameter and so on. E. g. at lower incident energies the scattering or emission angles can be large enough to start in the nucleus an internuclear cascade which can blow off a great portion of the nucleus. For higher energies it is rather justified to assume that the only result of the first "knock off" stage is, as far as the struck nucleus is concerned, a hole or a tunnel bored through the nucleus by the incident nucleon and the relativistic secondaries. The existence of such a tunnel, in which (Fig. 2) the smaller opening angle the greater is the incident energy can be justified by small binding energy of the nucleons in the nucleus in comparison to the very large energy of the incident nucleon and also by the very short duration of the "knock off" stage. The remaining recoil nucleus with a whole bored through it is, of course, highly excited. The excitation energy is quickly redistributed according to the laws of statistical thermodynamics (as it is believed). The excitation energy is usually high enough to justify the use of the simple statistical model of the nucleus by Fermi and to characterize this excited piece of nuclear matter by some temperature T. The second stage of the process which is supposed to be responsible for the omission of non-relativistic particles consists of the redistribution of energy till some kind of thermodynamic equilibrium characterized by the temperature T is reached. This stage ends with the evaporation of some number of nucleons or heavier fragments which carry off the excess of energy and allow the remaining nucleus to come to some metastable or even stable state. I should like to point out that there are substantial differences between the use of the statistical model for the excited nucleus and those applications of it to elementary nucleon-nucleon collision which were described by Prof. Hayakawa.

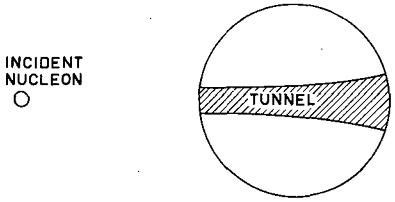

Fig. 2

Tunnel mechanism

Using the simple statistical model of the nucleus whose state is characterized by a very small number of parameters like temperature and total mass we can make certain predictions. If this model is correct one should expect isotropic emission of evaporated particles in the rest system of the recoil nucleus irrespective of their mass and energy. We can also calculate the energy distribution of particles of given mass as well as the frequency of emitting particles with different masses provided that the value of the excitation temperature T is known and roughly the same for all cases under consideration. The result of such estimations done with some reasonable assumptions about the value of T shows that for example the frequency of emission should drop quickly with the increasing mass of the emitted particles.

How do these predictions compare with the experiment? If one considers the angular distribution of all black tracks without trying to distinguish their masses one finds roughly isotropic distribution in the rest system of the recoil nucleus. In the laboratory system, there is, of course, some tendency for the forward emission, which can be understood as a purely kinematic effect of the finite recoil momentum. In other words during the first stage of boring the tunnel through the nucleus some amout of linear momentum must be transferred to the nucleus. It seems however, that sometimes the experimental values of this recoil momentum which are necessary to obtain isotropic distribution of black tracks exceed significantly the theoretically expected limits. This is, however, not a very serious disagreement.

More interesting phenomena come into light if we start to differentiate the emitted non-relativistic particles recording to their mass and energy. It has been found by several laboratories that the number of heavier fragments definitely exceeds the values found from the simple statistical model of evaporation. There is also some definite excess of energy carried off by these heavier fragments when compared with the values expected on the basis of the statistical model by Fermi. The third interesting deviation from the statistical model is the angular distribution of the heavier fragments which indicates preferential emission into the forward hemisphere with a maximum at some angles $\theta \neq 0$ but rather with $20^\circ < \theta < 80^\circ$.

We have, therefore to explain three deviations from the statistical model of the non-relativistic particles emission in high-energy nucleon-nucleus collisions:

a) excess in number of heavier fragments,
b) excess in energy of heavier fragments,
c) preferential angle of emission $\theta \neq 0$.

2. THEORETICAL EXPLANATION

Before going over to the proposed theoretical explanation of these facts I should like to stress that the experimental situation is by no means transparent. In spite of the fact that the first discovery of these deviations was made by Perkins quite long ago the existing statistics of such events is still not sufficient to tell us what are the angular and energy distributions of non-relativistic particles at different but fixed energies of the indicent nucleon. We also do not know very much about the dependence of these functions on the type of the struck nucleus, mass of the fragment etc. To have a more transparent picture one should have much more numerous statistics of events differentiated according to: 1) energy of the incident nucleon E_i, 2) type of the struck nucleus A, 3) mass of the emitted fragment M_f, 4) excitation energy ϵ of the recoil nucleus, 5) energy of the emitted fragment E_f, 6) angle of emission θ_f etc, etc. In the present experimental situation data referring to quite different values of the above experimental parameters are being put together which makes the theoretical analysis quite difficult and obscures the whole picture. In spite of the fact that we may wait a long time for more transparent experimental data we can extract already now some important results and try to make a theory which would be able to make some predictions.

Although the figures given by several laboratories are varying and cannot be simply compared for reasons stated above it seems that the very existence of the three deviations is beyond doubt and requires some theoretical explanation. One may first think that because of these deviations one must reject the simple statistical model completely. However, it seems that it works rather reasonably well as far as emission of nucleons is concerned. Therefore, it will be rather better to look for some additional mechanism which would be chiefly responsible for the emission of heavier fragments with the observed properties. In other words we shall assume that between the very quick "knock off" stage and the comparatively slow evaporation stage describing the emission of most nucleons we have to do with some process which immediately follows the "knock off" stage and ceases to work before the evaporation takes place. We may call this intermediate stage fragmentation. Thus we have to distinguish probably not two but three stages:

1) knock off of the relativistic particles,
2) fragmentation of the recoil nucleus,
3) redistribution of energy and evaporation of the recoil nucleus.

Just the second stage would be responsible for the creation of most heavier fragments with rather small contribution to the emission of nucleons described chiefly by the statistical evaporation model. To produce heavier fragments with observed excess energies and emitted at some preferential angles we need some long range forces which would be able to act coherently upon larger pieces of the nucleus without destroying the bounds between the nucleons in the emitted fragments.

The first thought is to make the internuclear cascade responsible for this phenomenon. However, the internuclear cascade of angles wide enough can evolve only at lower incident energies E_i. It would not work in the high energy region where there cannot be other cascade apart from the narrow jets of relativistic particles. But even at low energies one may rather expect that the internuclear cascade has the tendency of breaking everything into single nucleons than to act coherently upon larger pieces of nuclear matter. Calculations basing on the internuclear cascade as a possible mechanism of fragmentation show that we cannot fit the experimental data unless we assume the existence of some new long range forces.

Let us, therefore, start from another point. Let us look for a possible source of long range forces in the nucleon-nucleus scattering. (By "long range" I mean here a range exceeding several times the well known range

$\frac{1}{\mu}$ of nuclear forces). It seems to me that such a possibility exists due to the peculiar behaviour of the meson field accompanying a non-uniformly moving nucleon.

Let us consider the equation for the meson field φ created by some given source $\rho(\vec{x}, t)$

$$(\Box-\mu^2)\,\varphi\,(\vec{x}, t) = -\,4\pi\,\rho(\vec{x}, t). \tag{1}$$

If the source function is time independent (static) the solution we are usually interested in can be obtained by means of the static Greens function

$$g_0(\vec{x}, \vec{x}') = |\vec{x}-\vec{x}'|^{-1}\exp\{-\mu|\vec{x}-\vec{x}'|\}. \tag{2}$$

For the case of point source we obtain the well known Yukawa potential with well defined range of forces equal to $\frac{1}{\mu}$:

In the more general case of time dependent sources one can solve the equation (1) by means of similar Green's functions if one writes ρ and φ in the form of Fourrier integrals

$$\rho(\vec{x}, t) = \int_{-\infty}^{+\infty} \rho(\vec{x}, \omega)e^{i\omega t}d\omega,$$

$$\varphi(\vec{x}, t) = \int_{-\infty}^{+\infty} \varphi(\vec{x}, \omega)e^{i\omega t}d\omega,$$

and after inserting into (1) compares the coefficients at the same frequencies. One obtains in this way

$$[\Delta-(\mu^2-\omega^2)]\;\varphi\;(\vec{x}, \omega) = -\,4\pi\,\rho(\vec{x}, \omega). \tag{1.a}$$

The spherically symmetric Green's function for this equation has the form similar to (2) but the exponential is changed

$$g_\omega(\vec{x}, \vec{x}') = |\vec{x}-\vec{x}'|^{-1}\exp\{-\sqrt{\mu^2-\omega^2}\,|\vec{x}-\vec{x}'|\}. \tag{3}$$

One must, of course, be careful with taking the proper sign of the square root in (3). We see that for ω^2 increasing from 0 to μ^2 the range of forces transmitted by the ω component of the source is increasing from the minimum static value $\frac{1}{\mu}$ to infinity. For $\omega^2 > \mu^2$ we have to do with wave type solutions because in this region $\sqrt{\mu^2-\omega^2}$ is imaginary. This corresponds, of course, to the presence of real mesons propagated in accordance with the Green's function $|x-x'|^{-1}\exp ik|x-x'|$. The complete solution of the equation (1) can be now put into the form

$$\varphi(\vec{x}, t) = \int\int d\omega d_3x'\;\rho(\vec{x}', \omega)e^{i\omega t}\,\frac{e^{-\sqrt{\mu^2-\omega^2}|\vec{x}-\vec{x}'|}}{|\,1\vec{x}-\vec{x}'\,|} \tag{4}$$

We see that the components of the source corresponding to given frequency ω are multiplied by exponential factors of a range increasing rapidly with increasing $|\omega|$. The formula (4) is quite general and valid for any kind of sources. However, one cannot say much more about the general case since the result of the integration over ω, i.e. the interference effect between different ω's, cannot be predicted in the general case. One may, however, expect that in some cases we may be able to observe a realistic increase in the range of the mesonic field.

Let us come back to the case of high energy nucleon-nucleus collision. I am suggesting that the fragmentation stage is the result of the coherent action of the mesonic field accompanying the incident nucleon and distorted by its collisions with the other nucleons in the tunnel. The question immediately arises: can this distorted mesonic field have the proper range and shape necessary to describe the experimental data? The answer is not easy as the result of the calculation may depend in a very crucial way on the assumptions about ρ, i.e. on the time development of the "knock off" stage.

In order to see if there is any chance of describing the qualitative features of the fragmentation stage we have made in Warsaw some simple assumptions about ρ trying, however, to fit the free parameters to the experimental material in possession of the Warsaw cosmic ray group. Thus we have assumed that due to high energies the nucleon can be well localized and correspondingly one can justify the use of the "classical" source function

$$\rho(\vec{x}, t) \sim \delta_3(\vec{x} - \vec{\xi}(t))$$

with some prescribed law of motion given by the function $\vec{\xi}(t)$. We have assumed that the motion of the incident nucleon is uniform up to the point of the collision uniformly decelerated during the passage through the nucleus and again uniform after leaving the nucleus. The plot of the assumed nucleon velocity is on Fig. 3.

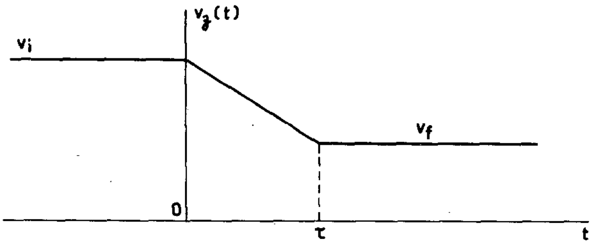

Fig. 3

Assumed velocity versus time plot

The free parameters like initial and final velocities, duration of the collision (resulting from the assumed size of the nucleus and central character of the collision) were taken from the experimental set up. Kaniowski, a student from Warsaw, has made preliminary calculations looking just for the shape of the mesonic field accompanying such a uniformly decelerated nucleon at a time shortly before it leaves the nucleus. The result of these calculations seems to be very encouraging. Fig. 4 shows the schematic plot of the

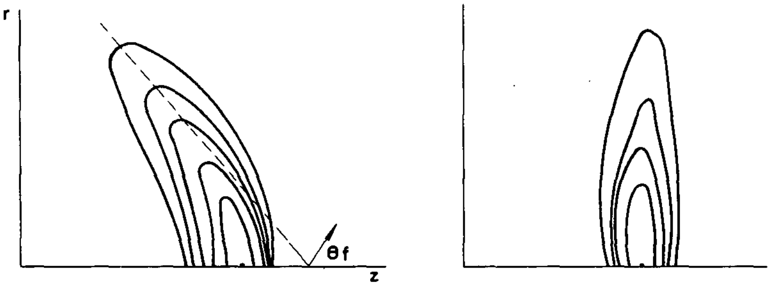

Fig. 4

Schematic plot of the shape of the curves φ = const. as a function of z and the distance π from the z-axis

shape of the curves (actually surfaces) φ = const as function of z and the distance $r = \sqrt{x^2 + y^2}$ from the z axis. On the right the corresponding plot for uniform motion is shown. For uniformly decelerated motion we have found that the meson field gets distorted into the right direction.

In fact some kind of shock wave is created. The "wings" of this shock wave extend as far as 4-5 fermis. For the assumed values of the free parameters the angle $\theta_f = 26.5°$ which fits quite well to the experimental value of the Warsaw cosmic ray group of ~30°. Of course, these results are very preliminary. We are now doing more elaborate calculation on an electronic computer aiming at a more detailed knowledge of the shape, time development of the shock wave, the energy carried by its "wings" etc. Unfortunately, I have not got the result of these more extensive calculation as yet.