Violation of nuclear scaling in heavy-nucleus interactions

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For central collisions of nuclei of the Ca-Fe group with an energy of 15–200 GeV/nucleon with Ag and Br nuclei, the slope of the energy spectrum of protons in the rear hemisphere in the energy region 100–400 MeV has been found to be sharply smaller than the slope of the spectrum in hadron-nucleus interactions.

We know that the energy spectra of protons in the rear hemisphere, $\theta > 90°$, in reactions of the type[1] $h + A \rightarrow p + X$ can be parametrized quite accurately in the following way for various energies of the incident hardrons (E^{in}), for various atomic weights of the target (A) (above certain values of E^{in} and A), and for various values of the angle θ:

$$f(E, \theta) = C\exp[-E(1 - \beta\cos\theta)/T_0], \qquad (1)$$

where E is the energy of the proton, $\beta \approx 0.5$, and $T_0 \approx 58$ MeV.

The universal validity of expression (1) for various initial energies E^{in}, various angles, and various atomic weights A reflects the occurrence of a "nuclear scaling" in hadron-nuclear interactions.

In the case of the pA interaction, the half-space $\theta > 90°$ is a part of the phase space which is forbidden to the secondary protons in a process which occurs during a proton-nucleon interaction. We follow the customary terminology in referring to these protons as "cumulative."

It is important to test for nuclear scaling in a far more complex process: central interactions of heavy nuceli. So far, this test can be carried out only through the use of cosmic-ray nuclei of the iron group, Ca-Fe, in interactions with Ag and Br nuceli in a nuclear emulsion.

Indications of qualitative changes in the energy spectra of all protons with energies of 30–400 MeV ($\theta = 0$–$180°$) in the reaction $A_1 + A_2 \to p + X$ were found some time ago, in Ref. 2, for nuclei with energies of 2–15 GeV/nucleon in the reaction (Ca-Fe) + Ag, Vr in which $n_{\rm int} \gtrsim 40$ nucleons of the incident nucleus were involved in the interaction. The exponent γ in the energy spectrum $I = aE^{-\gamma}$ turned out to be ~ 0.67, while that for proton-nucleus interactions is $\gamma \approx 1.3$–1.5. For events with $n_{\rm int} \approx 50$ the proton energy spectrum in the interval 100–400 MeV found at $E^{\rm in} \approx 15$–200 GeV/nucleon in this study is even harder: $\gamma + 0.3$. Such a sharp change in the slope of the spectrum (with a more gradual decrease in the exponent as $n_{\rm int}$ increase from 1 to ~ 40) is apparently a result of very nonlinear processes in the evolution of the space-time picture of the interaction in collisions of nuclei, including the particles which are emitted into the rear hemisphere.

For an actual comparison of experimental data on the proton spectra in the cumulative region, $\theta > 90°$, in the reaction (Ca-Fe) + Ag, Br (Ref. 3),

$$dN/dE = \varphi(E) \tag{2}$$

and in the process $p + A \to p^*_{\rm kym} + X$ (Ref. 1),

$$(1/p)(d^2\sigma/dEd\Omega) = f(E,\theta) \tag{3}$$

we should allow for the difference in the representation of these spectra. To put (3) in the same form as (2), we need to integrate expression (3) with a weight of $\sin\theta d\theta$ over the range 90°–180° and multiply by a factor of $p \approx E^{1/2}$. In the units of Ref. 3, the quantity f is then given approximately by

$$\mathcal{F}(E) \cong E^{1/2}\exp(-E/T_0^*), \tag{4}$$

where $T_0^* \approx 50$ MeV. Examining the resulting effective proton spectrum in the rear hemisphere in the hardon-nucleus reaction in the range 50–400 MeV, we then find $\bar{F}(50\ \text{MeV})/\bar{F}(400\ \text{MeV}) \approx 430$.

To compare the slopes of the proton energy spectra in the rear hemisphere in the interactions of nuclei with nuclei and of hadrons with nuclei, we used some of the interactions from Ref. 3, selecting only events in which the energy was between 3 and 15 GeV/nucleon. For the comparison, a straight line with an effective slope (4) for he $p + A$ interaction was normalized to the Ca–Fe + Ag, Br experiment at the point with $E = 50$ Mev, since nuclear scaling was described beginning at approximately this energy in Ref. 1. In the interactions of nuclei, the slope of the spectrum decreases (the triangles in Fig. 1). The difference, however, is still not great. Is the tendency toward a disruption of the scaling in the interactions of the nuclei confirmed as the statistical base is increased, as the energy of the interacting nuclei is increased, and as the impact parameter is reduced?

To resolve this problem, we studied 25 interactions of cosmic-ray nuclei with energies of 15–200 GeV/nucleon in the (Ca-Fe) + Ag, Br reaction in a nuclear emulsion. Events were selected on the basis of the following criteria: The number of highly

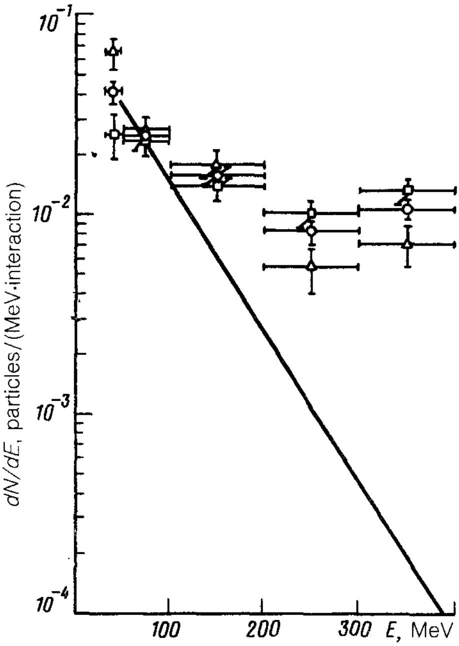

FIG. 1. Energy spectrum of the protons in the rear hemisphere in central Ca-Fe + Ag, Br interactions. Δ—25 events, $E^{in} \approx 3$–15 GeV/nucleon; □—36 events, $E^{in} \approx 15$–200 GeV/nucleon; O—overall distribution, 61 events. The straight line is the effective spectrum of protons in the rear hemisphere in the reaction $h + A \to p + X$, constructed from (4) and normalized to the spectrum of the protons in the resultant distribution in the interactions of nuclei at the point with an energy of 50 MeV.

ionizing particles from the target nucleus satisfied $N_h = N_g + N_b \geqslant 28$–30 with $N_b \leqslant 10$, where N_g and N_b are the numbers of protons (gray and black tracks) with energies of 30–400 MeV and 0–30 MeV. Such interactions correspond to a small impact parameter ($B \approx 2$–3 fm). We also studied 11 "anomalous" interactions of iron-group nuclei with a minimal impact parameter ($B \approx 0$–2 fm) with an energy of 15–25 GeV/nucleon. These interactions were selected for a maximum multiplicity of the relativistic particles and for the essential absence of spectator protons of the incident nucleus at the smallest emission angles, regardless of the number N_h.

In the interactions studied, the minimum ionization I_0 was set by the count of grains on the tracks of singly charged particles which were emitted at the smallest angles with respect to the direction of the incident nucleus, for each layer of the emulsion in which the interaction occurred and for the neighboring layer. On each track we counted from 400 to 1000 grains. An estimate of the energy was made for all gray and black tracks with $\theta < 90°$. For thin tracks with an ionization $I \leqslant 1.4 I_0$ we measured the grain density. The energy for protons with an energy $\leqslant 100$ MeV was found by following the tracks to the point at which they ended. For protons with energies from 100 to 400 MeV the energy was estimated from the grain density. For plane tracks with a slope < 10–$20°$ and an energy ~ 100 MeV the estimate of the energy on the basis of the range corresponded to an estimate of the energy on the basis of the grain density.

The proton energy spectrum corrected for the numbers of gray tracks in the various energy intervals (these corrections reflected the decrease in the ionization in the count of the grains on the tracks with a large slope) agrees with the energy spectrum found for the particles from tracks with a small slope, $< 30°$, with a subsequent geometric correction for tracks with large slopes.

It follows from Fig. 1 that the yield of protons with energies of 200–400 MeV doubles with increasing energy of the nuclei. The slopes of the proton energy spectra in the energy range 100–400 MeV in the interactions of heavy nuclei with $E^{in} > 15$ GeV/nucleon (the squares) and in interactions of hadrons with nuclei (the straight line) are quite different. This difference is made even more significant by the decrease in the errors when the data on the interactions of nuclei are summed over the entire energy range 3–200 GeV/nucleon (the circles). Consequently, in the interactions of heavy nuclei with an energy > 3 GeV/nucleon at small values of the impact parameter we are seeing a violation of the nuclear scaling: a statistically reliable and significant decrease in the slope of the proton energy spectrum in the cumulative region, $\theta > 90°$, from that corresponding to interactions of hadrons with nuclei.

We will offer a detailed interpretation of this observation of a violation of nuclear scaling in the interactions of heavy nuclei in subsequent publications. As a preview we note that in the interactions with a small impact parameter which were studied a stopping of a significant fraction of the inelastically interacting nucleons of both nuclei becomes possible, up to the point that they are completely stopped in the c.m. frame.[4] As a result, the trailing edges of the colliding nuclei will interact with nuclear matter of increased density. In the "collection" model,[5] for example, the effect would be to increase the yield of cumulative nucleons in the rear hemisphere in the laboratory and antilaboratory frames.

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