Maxima in the velocity spectra of the protons produced in interactions of high-energy nuclei

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Results are presented of experimental investigations of the velocity spectra of singly charged particles produced when particles of high energy (3.6 GeV/nucleon) interact with lead. The spectrum is observed to have a characteristic feature, namely a maximum at $\beta = 0.5$. The results are compared with the published data, with which they are in good agreement.

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Much attention has been paid in the last few years to phenomena occuring in nucleus—nucleus collisions at high energies of the incident particles (from several hundred MeV/nucleon to several GeV/nucleon). These collisions are characterized by a large particle density and large energy density in the interaction region. At present this is apparently the only method of producing in nuclear matter extremal conditions that differ greatly from the usual ones and make it possible to investigate the properties of nuclear matter in a wide range of temperatures and pressures. Great interest attaches to the possibility of appreciably condensing nuclear matter in such collisions and to the onset in this matter of motions of collective type.

The experimental research in this field is so far in the preliminary stage. The very first studies,[1] whose main purpose was to search for nuclear shock waves, yielded contradictory results. Many experimental data were obtained in Refs. 1–4, where the energy spectra of secondary particles emitted when heavy nuclei are bombarded by accelerated ions (from α particles to argon nuclei) were measured at various angles.

We thought it useful to investigate the velocity spectra of the reaction products, since these spectra should reveal primarily the hydrodynamic aspects of the processes of production and decay of highly excited nuclear matter inasmuch as hydrodynamic motion is characterized by directional fluxes that determine the velocities of the par-

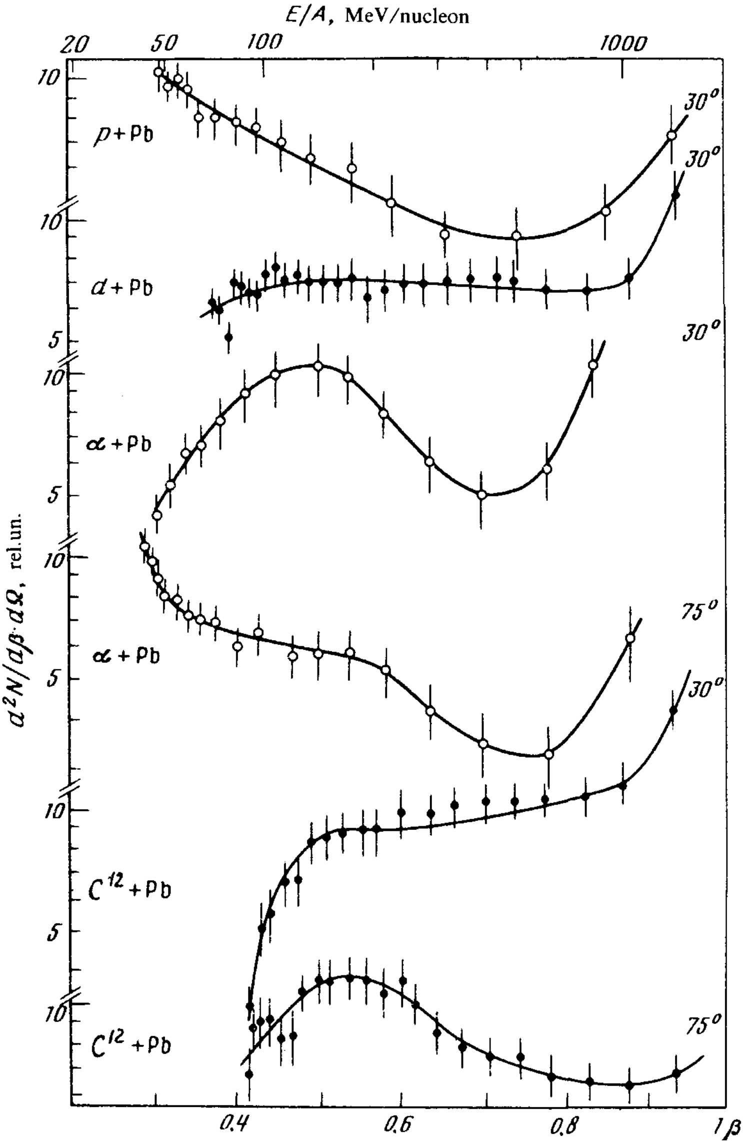

FIG. 1. Velocity spectra of singly charged particles emitted in interactions of p, d, α, and C^{12} of energy 3.6 GeV/nucleon with a lead target.

ticipating particles. This has in fact dictated the choice of the experimental procedure—measurement of the time of flight of the secondary particles and of the energy released in one of the detectors. Such a system measures the particle velocity and at the same time identifies it by charge. The experimental method, the reduction procedure, and the analysis of the experimental data will be described in detail in a separate article. This method made it possible, in addition, to cover a wider range of emitted-particle energy (v from 0.3 c to c) than in experiments with total absorption (the ΔE–E procedure),[3] a particularly important factor during the initial stage of the work.

Results of investigations of the velocity spectra of the products of the interaction between α particles of energy 3.6 GeV/nucleon and a lead target, obtained with the proton synchrotron of the High-Energy Laboratory of the Joint Institute for Nuclear Research, were published earlier.[5] In these spectra, besides the maximum at $\beta \approx 1$ due to the produced pions,[6] there was a clearly pronounced maximum at $\beta \approx 0.45$–0.5 at small observation angles ($\sim 30°$), which become smoothed out when the angle was increased to 75°. We have subsequently performed experiments on the velocity spectra of the secondary particles emitted when a lead target is bombarded with protons, deuterons, and C^{12} nuclei having the same energies per nucleon as the α particles. The results of these investigations, together with the data of Ref 5., are shown in Fig. 1. It is easily seen that whereas for the experiment with incident protons in the region of β from 0.3 to the position of the pion peak the observed spectra decrease smoothly with increasing β and have no singularities, in the case of bombardment by α particles or C^{12} nuclei the velocity spectra of the singly charged particles are a maximum at an observation angle 30°. This maximum is more clearly pronounced if C^{12} ions are used and is located at $\beta \approx 0.5$ but is also observed, albeit less clearly, at 75°. The spectra obtained by deuteron bombardment present so to speak an intermediate picture between the case of protons and heavier incident particles. The relative fraction of the emitted pions also decreases with increasing angle.

A surprising singularity of the obtained spectra, besides the very existence of the maximum, is the absence of a dependence (or a very weak dependence) of their position first, on the total energy of the incident particle, and second on the observation angle.

This result patently contradicts the fireball model,[2] which is widely used at present to describe nuclear interactions at high energies.

To ascertain whether the observed effect is peculiar to energies of order of 4 GeV/nucleon, we have analyzed a number of the published experimental data obtained with the Bevalac accelerator (Berkeley, California) with the aid of beams of various heavy ions (from He^4 to Ar^{40}) in the per-unit energy range 0.25—2.1 GeV/nucleon. The measurement procedure made it possible to register secondary singly charged particles in the energy interval 20—200 MeV/nucleon. The energy spectra given in Ref. 3 were converted by us into velocity spectra. Some of these spectra are shown in Fig. 2. It is easily seen that the character of the curves is similar to the character of the curves from our experiments. The same singularities are observed: maxima exist at $\beta \approx 0.5$; the position of the maximum does not depend or depends weakly on the total energy of the incident particle; the maximum for the reaction $Ne^{20} + U$ becomes smoothed out at larger angles and at relatively small energies 250

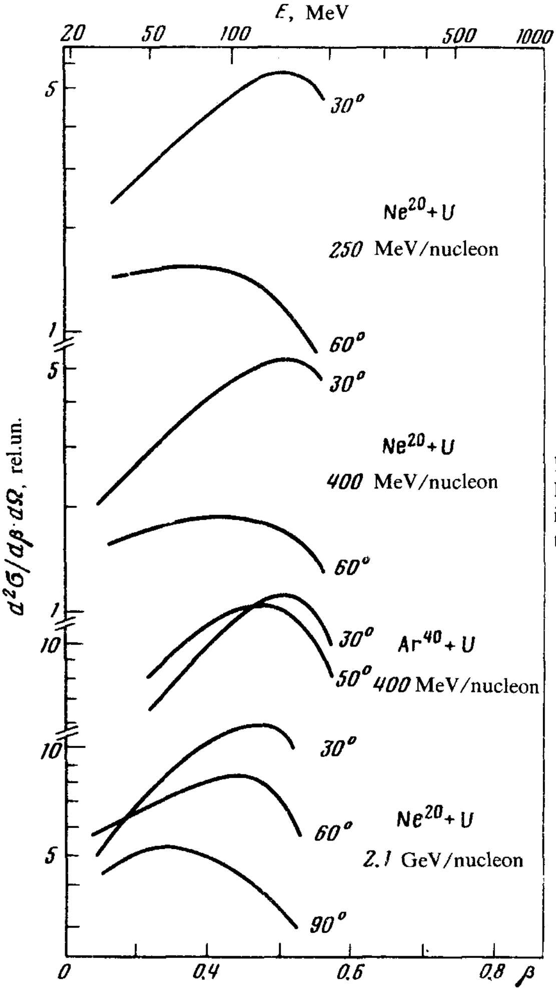

FIG. 2. Velocity spectra, obtained by recalculation of the data of Ref. 3, of protons emitted in interaction of Ne^{20} or Ar^{40} with a uranium target.

and 400 MeV/nucleon; its position depends very little on the scattering angle in the interactions of Ne^{20} and Ar^{40} with U nuclei at large total energies (2.1 GeV/nucleon) and 400 MeV/nucleon), respectively.

It should be noted that so far we have dealt with inclusive spectra, although great interest attaches to the change that occurs in the picture when events with high multiplicity are picked out. Data of this type were converted by us into a velocity representation. The results of the reduction point to the presence of a maximum in the velocity spectra at small observation angles, but it is still difficult to deduce its position.

In conclusion it must be stated that the origin of the maximum in the velocity spectra has not yet found its due theoretical explanation. It is only clear that this form and behavior of the velocity spectrum with changing observation conditions cannot be described on the basis of the fireball model, nor on the basis of the so called firestreak model, which is a development of the former. Further more extensive experimental and theoretical investigations are needed for a complete understanding of the occuring phenomena.

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