Brief Reports

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Onset of helium-fragment scaling in heavy-ion collisions

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Evidence for the onset of Koba, Nielson, and Olesen scaling at low energies for helium fragments produced in heavy-ion collisions is presented.

In heavy-ion collisions, we know that the most abundant projectile fragments are protons and helium particles. It is important to know on the average how many projectile helium particles are produced in an interaction, in different heavy-ion beams, at about the same energy per nucleon. Does the multiplicity of these fragments observe any kind of scaling? In order to answer this question we exposed a number of Ilford G-5 emulsion stacks to various heavy-ion primary beams from the Bevatron at Lawrence Berkeley Radiation Laboratory. The primary beams used are C at 400 MeV/nucleon, Ne at 300 MeV/nucleon, Si at 463 MeV/nucleon, Ar at 1.9 GeV/nucleon, Fe at 0.9 GeV/nucleon and 1.9 GeV/nucleon, Kr at 0.9 GeV/nucleon and at 1.52 GeV/nucleon. For this experiment, the data used for different beams are in the energy interval 400–300 GeV/ nucleon for C, 300–150 GeV/nucleon for Ne, 463–250 GeV/nucleon for Si, 1.9–1.0 GeV/nucleon and 0.9–0.5 GeV/nucleon for Ar, 1.9–1.0 GeV/nucleon and 0.9–0.5 GeV/nucleon for Fe, 1.52–1.0 GeV/nucleon and 0.9–0.5 GeV/nucleon for Kr, respectively. Scanning was done by along-the-track method under high magnification.[1] An incident track was followed until it interacted, stopped or left the pellicle, in which case it was followed to the next pellicle. Depending upon their visual characteristics, the interactions were classified as (a) projectile fragmentation alone with no visible target fragmentation known as "white star" with $N_h = 0$ (N_h is the number of nonrelativistic tracks) which contributes about 12% to the population of events, (b) target fragmentation only with no detectable change in the charge of projectile which contributes about 5% to the population, (c) projectile breakup with target breakups due to the evaporation of the particles from the target ($N_h \geqslant 1$). The majority of the primary events belong to this category. Helium particles, with which we are mostly concerned here, were identified by δ-ray density or by grain density and/or by gap density measurements.[2] We show in Fig. 1 a very interesting relation between the mass number (A) of the beam and the average helium multiplicity, i.e. $\langle n_\alpha \rangle = 0.62 A^{0.33}$ for different primary projectiles in nuclear emulsions. In Fig. 1 is also shown the average proton multiplicity, i.e. $\langle n_p \rangle = 0.74 A^{0.53}$ for different projectiles.

The multiplicity distribution of hadrons produced in high energy particle collisions has been regarded as a source of information about the underlying production processes. Various models of the hadron production process in a hadron-hadron collision have led to the predictions of the multiplicity distribution. Within the last decade, the Koba-Nielson-Olesen (known as KNO) scaling hypothesis[3] has become the dominant framework to study experimentally[4] and theoretically[5] the behavior of the multiplicity distribution of secondary hadrons produced in high energy collisions. This hypothesis was originally derived assuming Feynman scaling of the inclusive particle production cross section. It states that the multiplicity distribution in the form

$$\psi(Z) = \langle n \rangle \sigma_n / \sigma_{\text{inel}} \tag{1}$$

should become asymptotically an energy-independent function of $Z = n/\langle n \rangle$, where n refers to the number of charged particles in an event and $\langle n \rangle$ is the average charged-particle multiplicity. σ_n is the partial cross section for producing a state of multiplicity n, and σ_{inel} is the total inelastic cross section. It is well known that the shape of function ψ remains approximately constant with the changes in energy

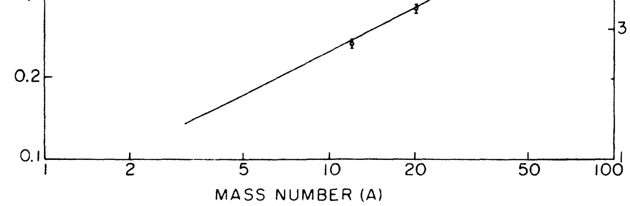

FIG. 1. Plot of average number of (i) helium fragments $\langle n \rangle$ vs the mass number A, (ii) proton fragments $\langle n_p \rangle$ vs the mass number A.

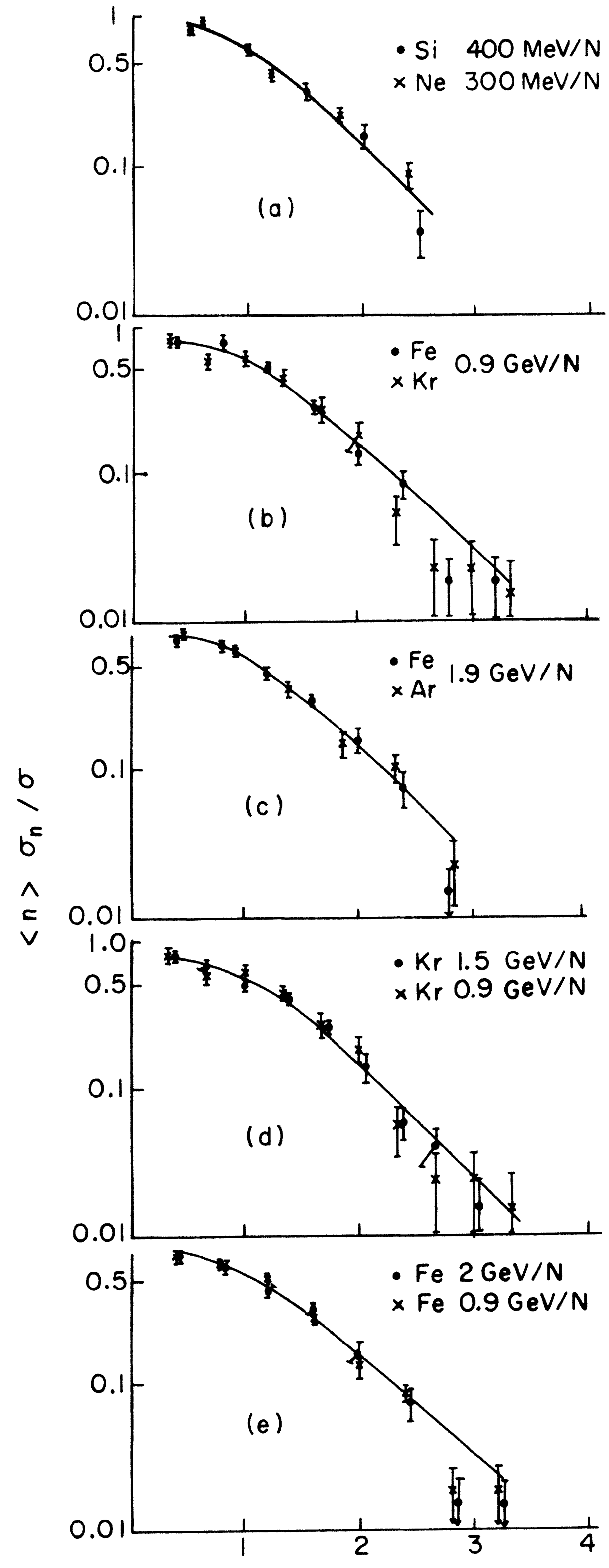

FIG. 2. Plots of $\langle n\rangle\sigma_n/\sigma$ vs $n/\langle n\rangle$ for helium fragments for different projectiles in emulsion: (a) Ne at 400 MeV/nucleon and Si at 300 MeV/nucleon, (b) Fe and Kr at 0.9 GeV/nucleon, (c) Fe and Ar at 1.9 GeV/nucleon, (d) Fe at 0.9 and 1.9 GeV/nucleon, and (e) Kr at 0.9 and 1.5 GeV/nucleon. Solid curves in these figures are due to Eq. (1) in the text.

TABLE I. Values of the fitted coefficients in Eq. (2).

Projectile	Energy (GeV/nucleon)	Value of the coefficients A	B	χ^2/D.F.
Ne,Si	0.3	5.39 ± 0.36	2.18 ± 0.08	1.15
Fe,Ar	1.9	4.47 ± 0.15	2.02 ± 0.04	0.45
Fe,Kr	0.9	4.21 ± 0.28	1.99 ± 0.08	1.04
Fe	0.9	4.27 ± 0.14	1.99 ± 0.04	0.44
	1.9			
Kr	0.9	4.19 ± 0.26	2.00 ± 0.07	1.13
	1.5			

from $\sqrt{S}=1.5$–63 GeV. For the first time we extended KNO scaling[6] to nucleon-nucleus and then to nucleus-nucleus[7] interactions at high energies ($E\sim1$ GeV/nucleon). From the experimental results, we concluded that the KNO scaling behavior of the multiplicity distributions are well satisfied by the produced hadrons at different energies. Early scaling seems to indicate that certain factors in the production mechanism are already stabilized. It will be interesting to see, for the first time, if we can extend the KNO scaling to nucleus-nucleus interactions now at low energies for the inclusive spectra of helium particles produced from different primary projectiles. In Fig. 2(a) is shown the plot of $\langle n\rangle(\sigma_n/\sigma)$ vs $n/\langle n\rangle$ for helium particles produced by Ne and Si beams at about 150–450 MeV/nucleon energy range in nuclear emulsion. Our experimental points lie on a solid curve which is given by a universal function,

$$\psi(Z)=AZe^{-BZ}\ . \tag{2}$$

The values of A and B are 5.39 ± 0.36 and 2.18 ± 0.08, respectively, and χ^2/D.F. is 1.33. If we disregard the experimental point, from the tail part of the curve where the statistics is poor, then χ^2/D.F.$=1.15$. Similar plots for Fe and Kr at 0.9 GeV/nucleon, and for Fe and Ar at 1.9 GeV/nucleon are shown in Figs. 2(b) and 2(c), respectively. The values of the coefficients and χ^2/D.F. (after removing the experimental points in the tail) are listed in Table I. The value of χ^2/D.F. is around 1 which indicates that the fitting is good for different projectiles at the same energy. In Figs. 2(d) and 2(e), we show the plots of Kr and Fe, respectively, at different energies. Again the results of the fittings are given in Table I. From this table we see that the values of the coefficients for different projectiles at different

TABLE II. Moments of the multiplicity distribution.

Beam	Energy (GeV/nucleon)	C_2	C_3
Kr	1.5	1.38 ± 0.05	2.37 ± 0.09
Kr	0.9	1.38 ± 0.07	2.37 ± 0.09
Fe	1.9	1.35 ± 0.06	2.25 ± 0.10
Fe	0.9	1.35 ± 0.07	2.28 ± 0.09
Ar	1.9	1.34 ± 0.06	2.19 ± 0.10
Si	0.4	1.32 ± 0.06	2.21 ± 0.09
Ne	0.3	1.30 ± 0.06	2.11 ± 0.09

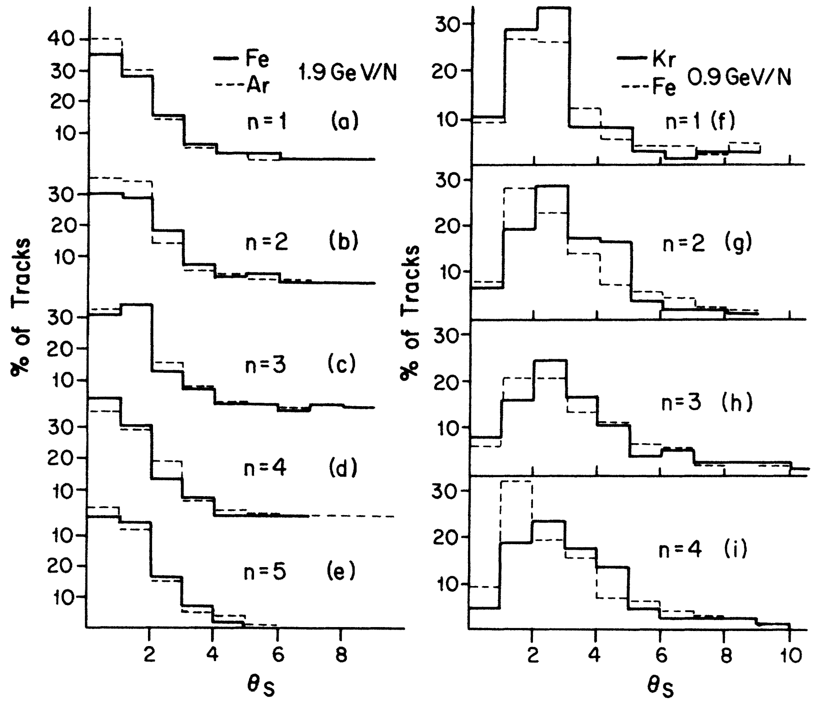

FIG. 3. The comparison of angular distributions of helium fragments at the same energy per nucleon for different helium multiplicities as indicated in the diagrams: (a)–(e) for Fe and Ar at 1.9 GeV/nucleon and (f)–(i) for Kr and Fe at 0.9 GeV/nucleon.

energies are very close to one another. This shows that helium fragments from different projectiles and at different energies obey the scaling function given in Eq. (1).

Another measure of the multiplicity distribution can also be studied using the moments of the distribution, i.e., $C_q = \langle n^q \rangle / \langle n \rangle^q = \text{constant}$. Exact KNO scaling implies that all C_q moments for alpha particles are energy independent,[3] since $C_q = \langle n^q \rangle / \langle n \rangle^q = \langle Z^q \rangle = \int Z^q \psi(z) dZ$. In Table II, we present the experimental values of C_q for $q=2$ and 3 for different beams. The ratios are consistent with being constants within their statistical limits. These results are quite interesting. As far as we know, this is the first time that the inclusive data of relativistic helium particles produced in heavy-ion collisions have been shown to follow the KNO scaling. This scaling points towards the universality of scaling in multiple production of charged particles in high energy inelastic collisions.

Apart from the multiplicities, we also looked at the angular distributions of He particles produced from Ar, Fe, and Kr beams at different energies. For alphas we measured the projection and the dip angles and from this we calculated space angles of these particles with respect to the primary beam on Koristka microscope with an accuracy better than 0.5°. In Figs. 3(a)–3(e) and 3(f)–3(i) are shown the angular distributions for different multiplicities of α's, with respect to the primary beams of Fe and Ar at about 2 GeV/nucleon and Fe and Kr at about ~ 1 GeV/nucleon, respectively. These distributions are quite similar for different projectiles when compared at the same energy per nucleon.[8] They shed some light on the structure of these heavy elements indicating that α-particle clusters play an important part in the nuclear structure of heavy ions.

We conclude that in heavy-ion collisions, alphas are produced in abundance as compared to the rest of the heavy fragments (i.e., $Z > 2$), with mean multiplicities given by the relation $\langle n_\alpha \rangle = 0.62 A^{0.33}$. For the first time we have shown here, the onsetting of early KNO scaling for helium particles, produced in nucleus-nucleus collisions. Early scaling at low energies seems to indicate that certain factors in the production mechanism are already stabilized. But at the present time, an apparent success of KNO scaling should be viewed as an experimental fact.

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