special state, related to a fluctuation of the nuclear density, composed of N nucleons ($N=2, 3, 4, \ldots$). However, the nucleons composing the fluctuons are assumed to be confined to a very small volume whose radius is smaller than the radius of a nucleon. Although such a state is unknown in nuclear physics, the picture has one advantage over my model, since the fluctuons automatically satisfy the only condition which exists in my model, namely, that the CC does not break up during the fast collision. In other words, the fluctuons are geometrically so small that the nucleons in each fluctuon interact with the incident protons simultaneously. On the other hand, it is found in my model that the mean distance between the nucleons composing the CC is almost the same as the correlation length which is usually found in nuclear structure calculations. In this respect, it may be said that the CC has more reality in the nucleus than the fluctuon.

I have shown that a model which takes into account collisions between the incident proton and correlated clusters is quite successful for explaining the backward-scattering problem. Further studies of this kind would be quite useful for exploring new features concerning correlations in nuclei.

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Universal Fragment-Momentum Distribution in High-Energy Nucleus-Nucleus Collisions[a]

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Fragments with $1 \leq Z \leq 12$, some with energies as low as 3 MeV/nucleon and some with energies as high as 120 MeV/nucleon, have been analyzed in high-energy nucleus-nucleus reactions with C, Ne, and Ar projectiles. For a given projectile the invariant cross sections *of all fragments* appear to define a "universal" curve that is exponential in momentum, provided momentum is evaluated in a frame in which the distribution is isotropic. The low speed of the frame ($\sim 0.01c$ to $\sim 0.1c$) suggests emission from the recoiling target.

Recently we reported[1] energy and angular distributions of complex nuclei ($3 \leq Z \leq 9$) with energies ~15 to ~60 MeV/nucleon produced in high-energy nucleus-nucleus interactions at the Lawrence Berkeley Laboratory Bevalac. The angular distributions were consistent with isotropic emission from a source moving in the beam direction with a very low velocity, $\beta_0 \approx 0.08 \pm 0.02$. The energy distributions in the moving frame were about equally consistent with Maxwellians with a very high temperature, $\tau \approx 50$ to 70 MeV, or with exponentials in momentum, the latter implying a nonthermal process. We pointed out that a source in thermal equilibrium at such a high temperature and low velocity would be incompatible with energy-momentum conservation and concluded that most of these complex nuclei must have been emitted nonthermally.

Much of the yield of the copiously produced H and He isotopes[2,3] may also be of nonthermal origin. We showed[1] that the yields of all fragments studied, from $A=1$ through 19, can be accounted for by two sources—(1) a fast, thermal source called a nuclear fireball,[2] with velocity and temperature fixed by energy-momentum conservation and simple geometric and thermodynamic considerations, and (2) a slow, nonthermal source. The relative contribution of the slow source increases from ~50% for protons to ~90% for ^{4}He and to ~100% for the complex nuclei.

In this Letter we show that the momentum distribution of fragments from the slow source appears to be a universal curve, exponential in form, for all species near the stability line, at least up to mass 19.

Figure 1 shows the invariant cross section, $f \equiv P^{-1} d^2\sigma/dE\, d\Omega$, as a function of P', the momentum in a frame moving at $\beta_0 = 0.08$. The open and closed symbols refer to the two inclusive reactions 400-MeV/nucleon-Ne + U → X + anything and 500-MeV/nucleon-Ar + Au → X + anything, where X is one of the species ^{8}Li (detected visually by its distinctive "hammer" track from the decay $^8\mathrm{Li} \rightarrow {}^8\mathrm{Be} \rightarrow 2\alpha$), and B, C, N, O, or F (its charge but not mass determined by its ionization rate). The data were reported in Ref. 1. With a Lorentz transformation using a single value of the source velocity determined by a least-squares calculation to be $\beta_0 = 0.08$, all of the data from a given reaction lie within a factor of 3 of a single exponential curve

$$f \equiv P^{-1} d^2\sigma/dE\, d\Omega = K \exp(-P'/P_c), \tag{1}$$

where

$$P' = \{\gamma_0^2[P_{\parallel} - \beta_0(P^2 + M^2)^{1/2}]^2 + P_{\perp}^2\}^{1/2}, \tag{2}$$

and the characteristic momentum $P_c = 236$ MeV/c for the Ne + U reaction and $P_c = 340$ MeV/c for the Ar + Au reaction. Thus, for a given reaction the invariant cross section for any charge from 3 to 9 at a given momentum is predicted rather well by three parameters, K, P_c, and β_0, that are independent of Z, A, and β', the fragment velocity in the moving frame.

As Fig. 2 shows, the "universal" exponential relationship in Eq. (1) seems to have broader applicability than just to heavy fragments with kinetic energies of a few tens of MeV/nucleon. We find that data for H and He isotopes with energies from ~20 to ~120 MeV/nucleon produced in 400-MeV/nucleon Ne + U reactions[2,3] lie on an extension of our curve for complex nuclei in the same reaction. We also find that complex nuclei with

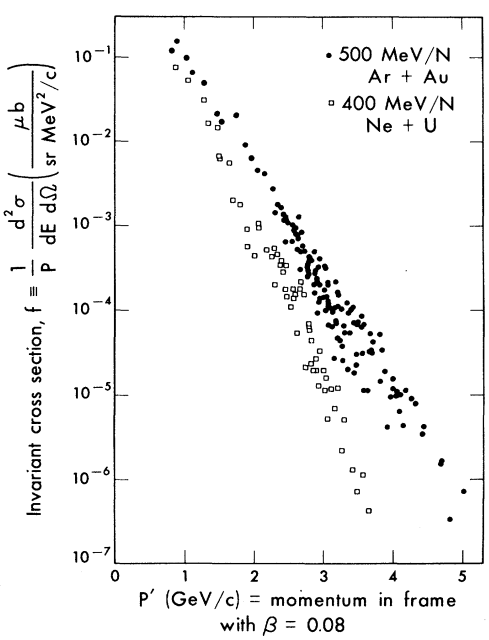

FIG. 1. Invariant cross sections for fragments ranging from ^{8}Li to fluorine as a function of total momentum evaluated in a frame moving in the beam direction with speed $0.08c$. Data are from Ref. 1.

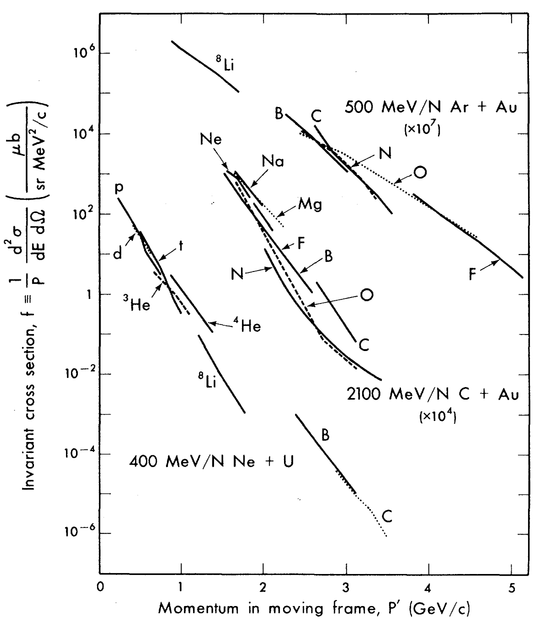

FIG. 2. Invariant cross sections for fragments from three different reactions. Data for p, d, t, ^{3}He, and ^{4}He are from from Refs. 2 and 3. In the C + Au reaction the data for B, C, N, and O are from Ref. 4. Remaining data are ours.

Z from 3 to 12 at energies all the way from 3 up to ~50 MeV/nucleon from the 2.1-GeV/nucleon C + Au reaction (data from Ref. 4 and our own unpublished measurements) are consistent with a single exponential in momentum.

Figure 2 differs from Fig. 1 in two ways. First, it identifies the curves for the different species so that one can see the range of momenta for which measurements of each species have been made. Second, it takes into account the experimental fact that, over the wide range of fragment energies from 3 to 120 MeV/nucleon, the source velocity β_0 in which the emission is isotropic is not a constant as was assumed to Fig. 1 for data in the narrower interval 15 to 60 MeV/nucleon. As we showed in Ref. 1, β_0 increases slowly with β', ranging from ~0.01 for fragments of a few MeV/nucleon to > 0.1 for fragments with > 100 MeV/nucleon. Intuitively this is not surprising if the fragments are coming from the struck, recoiling target nucleus. One expects fragments with highest energy to be emitted in collisions in which the most momentum is deposited in the target.

To compute P' for the data in Fig. 2 we determined the dependence of β_0 on β' by a relativistically correct analysis of contours of constant invariant cross section in momentum space. For isotropic emission from a source moving with Lorentz factor γ_0, the contour should be ellipsoidal in shape, with minor axis P' and major axis $\gamma_0 P'$, and displaced in the beam direction by $P_0 = M\beta_0\gamma_0$. The relation between P_0, P, and P' is given by Eq. (2). In a preliminary graphical analysis we confirmed that in general the contours were approximately circular, indicating isotropic emission (γ_0 always being ≈ 1), and we found that with increasing invariant cross section their radii, P', increased roughly linearly with their displacement, P_0, from the origin. To obtain the curves of f vs P' plotted in Fig. 2 we used a least-squares program to fit ellipses to the contours using relativistic transformations.

At high energies the contours for protons and ^{4}He were far from isotropic, having an additional component in the forward direction that might be interpreted as a contribution from a fast fireball. Despite the resulting large uncertainty in P_0, the uncertainty in P', the quantity used in Fig. 2, was small.

With a simple linear relation $\beta_0 = a + b\beta'$ (discussed years ago for proton reactions[5]), which increases the number of parameters to four (K, P_c, a, and b), the exponential momentum relation appears to apply to fragments with mass from 1 to ~20 amu and with kinetic energies from ~3 to 120 MeV/nucleon.

It is not surprising that the deviations from a single exponential line are sometimes large. Some of this is due to systematic as well as statistical errors in the data, but some is obviously due to the use on the same plot of data for single isotopes of a given charge. We expect that as more data for individual nuclides on the stability line become available, the deviation from a universal line will decrease if only the most stable nuclides are considered (e.g., ^{7}Li should lie above ^{8}Li; ^{11}B obviously will lie below the sum of all B isotopes).

The values of P_0 are ~280 MeV/c for the 500-MeV/nucleon Ar + Au reaction and ~160 MeV/c for the Ne + U and for the C + Au reactions. The values of β_0 for the 2100-MeV/nucleon reaction are considerably lower than for the reactions at 400 and 500 MeV/nucleon (see Ref. 1). This is exactly what one would expect: Target nuclei are more transparent and take up less momentum when struck by multi–GeV/nucleon nuclei than by medium-energy nuclei.

We have applied this same analysis to the published[5] fragment yields from the reaction 5.5-GeV $p + \mathrm{U} \to X +$ anything. The invariant cross sections for the various fragments from p to Ar fall off roughly exponentially with momentum, with P_c ~100–150, but fail by many orders of magnitude to lie on a single curve. When fitted to Maxwellian distributions in the moving frame, the apparent temperatures[5] are of order 10 to 20 MeV, very much lower than the apparent temperatures for nucleus-nucleus collisions. We conclude that there may be a qualitative difference between nucleus-nucleus collisions and proton-nucleus collisions, one manifestation of which is a universal fragment-momentum distribution for nucleus-nucleus collisions.

Exponential momentum distributions are, of course, not new. For many years it has been known that pions and other particles produced in high-energy pp collisions have roughly exponential transverse-momentum distributions.[6] It would seem to us worthwhile to explore possible similarities between the view of partons as constituents in hadron-hadron collisions and the view of nucleons and nucleon clusters as constituents in nucleus-nucleus collisions.[7] Recently Frankel[8] has interpreted his yields of protons and larger fragments at 180° in proton-nucleus collisions as evidence for an exponential tail on the internal momentum distribution of nucleons and light clusters.

Whether either of these distributions is relevant to our fragment-momentum distributions remains to be established. It is possible that the apparent regularities in Figs. 1 and 2 are accidental. Measurements of individual nuclides over a wider range of masses and momenta and for additional reactions would enable us to evaluate the significance of the apparent universal distribution.

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Nuclear Shape Staggering in Very Neutron-Deficient Hg Isotopes Detected by Laser Spectroscopy[a]

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The isotope shifts of ^{188}Hg, ^{186}Hg, and ^{184}Hg in the 2537-Å line have been measured by use of a tunable dye laser at the on-line mass separator ISOLDE at CERN. The results are $\delta\nu(^{188}\text{Hg}-^{204}\text{Hg}) = 35.8(2)$ GHz; $\delta\nu(^{186}\text{Hg}-^{204}\text{Hg}) = 39.4(2)$ GHz; and $\delta\nu(^{184}\text{Hg}-^{204}\text{Hg}) = 43.1(2)$ GHz. These data combined with those obtained by β-radiation–detected optical pumping (β-RADOP) on the odd Hg isotopes yield a huge odd-even staggering for ^{185}Hg of $\gamma = (2\delta\nu^{185/184})/\delta\nu^{186/184} = 13(1)$ which has to be interpreted as nuclear shape staggering.

A sharp onset of nuclear deformation of $\delta\langle\beta^2\rangle^{185/187} = 0.054(5)$ has been discovered between ^{187}Hg and ^{185}Hg by measurements of the isotope shift (IS) $\delta\nu$ with the β-RADOP (β-radiation–detected optical pumping) technique.[1-3] Hartree-Fock[4] and Strutinski calculations[5-7] have interpreted this finding as transition from a slightly deformed oblate shape ($A \geq 187$) to a strongly deformed prolate shape ($A \leq 186$). γ spectroscopy of ^{188}Hg,[8,9] ^{186}Hg,[10-12] and ^{184}Hg[13,14] has yielded evidence for a coexistence and crossing of two bands in these nuclei, one built on an almost spherical shape and one on a strongly deformed shape. The ground states have been found to belong to the vibrational band. Thus a strong odd-even staggering of the nuclear shape occurs in the light Hg isotopes. Recently, this staggering could be explained theoretically.[15-16] However, a quantitative interpretation of the shape transition and of the shape staggering calls for a model-independent measurement of these effects by one and the same observable, e.g., by the change of the nuclear charge radius $\delta\langle r^2\rangle$ as determined by IS experiments. Since RADOP fails in the case of $I = 0$ isotopes, purely optical techniques have to be used. Recently, an experiment on ^{190}Hg was reported which made use of a tunable dye laser in order to measure $\delta\nu$ in the $6s^2\,{}^1S_0$-$6s6p\,{}^3P_1$, $\lambda = 2537$ Å transition.[17] The same technique has now been extended to the lighter even-even isotopes ^{188}Hg, ^{186}Hg, and ^{184}Hg.

The experimental setup will be recalled very briefly (for details see Ref. 17). The dye laser is pumped by a 400-kW pulsed nitrogen laser. Laser light in the ultraviolet is generated by frequency doubling in an ammonium dihydrogen phosphate crystal. The laser beam passes a resonance cell, which is periodically filled with the isotope under investigation. Isotopically pure samples are obtained by the ISOLDE II facility,[18] an isotope separator on line with the 600-MeV synchrocyclotron at CERN. The intensities of the mass-separated ion beam, as obtained in the actual experiment, are given in Table I.