pletely eliminate the strange negative dip in $\bar{\epsilon}_1$ seen in recent multienergy analyses.[13]

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†Associated Western Universities Fellow.

‡Present address: Clinton P. Anderson Meson Physics Facility Visitors Center, Los Alamos, N. Mex. 87545.

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Evidence for Slowly Moving, Highly Excited Nuclear Matter Produced in High-Energy Nucleus-Nucleus Collisions*

J. Stevenson, P. B. Price,† and K. Frankel
Department of Physics, University of California, Berkeley, California 94720
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In the reactions 20-GeV Ar + Au and 8-GeV Ne + U, the angular and energy distributions of six nuclei with $Z \geqslant 3$ imply approximately isotropic emission from systems moving at $\beta_0 \approx 0.04$ to 0.11. The invariant cross sections fit either Maxwellians ($\tau \approx 52$ to 65 MeV) or exponentials in momentum ($P_0 \approx 240$ to 300 MeV/c) in the moving frame. The low β_0 and high τ are inconsistent with emission of nuclei ($Z \geqslant 3$) from a recoiling fireball unless extreme assumptions are made; they thus imply nonthermal emission.

Yields of complex nuclei with kinetic energies up to ~70 MeV/nucleon have been reported in a previous high-energy nucleus-nucleus experiment,[1] but because of the rather crude charge resolution and limited data, little could be learned about the nature of the source of these complex nuclei. With improved charge resolution and more extensive data for two different reactions, we can use the energy and angular distributions of complex nuclei as diagnostic tools to probe the mechanisms of high-energy nucleus-nucleus collisions. In this Letter, we present evidence that complex nuclei with energies between ~15 and ~60 MeV/nucleon are emitted from nuclear matter that appears to have a very high temperature ($\tau \gtrsim 60$ MeV) and a low lab velocity ($\beta \lesssim 0.1$). We will discuss the implications of a system with an apparent high τ and low β.

Figures 1 and 2 show our data for complex nuclei observed in the two inclusive reactions 500 MeV/nucleon ^{40}Ar + Au → ^AZ + anything, and 400 MeV/nucleon ^{20}Ne + U → ^AZ + anything. (In the latter reactions, yields of H and He isotopes were recently reported.[2]) The beam fluences were 1×10^{11} Ar nuclei and 7×10^{11} Ne nuclei from the Lawrence Berkeley Laboratory Bevalac. The targets were foils of 50-μm Au and 125-μm U at 45° to the beam. We used stacks of 75-μm Lexan detectors, placed at various angles with respect to the beam, to identify particles with $Z \geqslant 3$ that

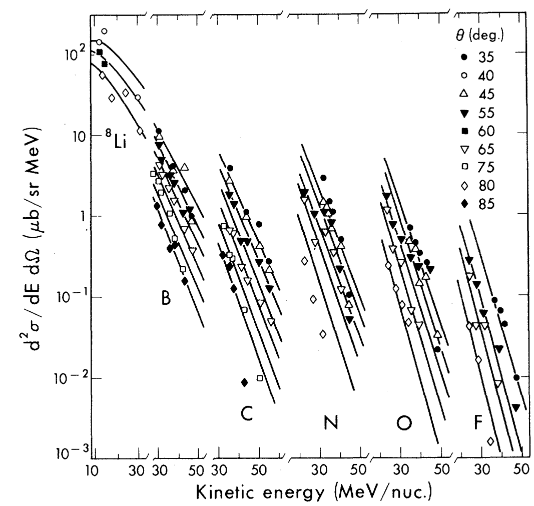

FIG. 1. Yields of complex nuclei produced in irradiation of gold by ^{40}Ar nuclei at 500 MeV/nucleon. The lines are calculated from Eq. (1) as explained in text.

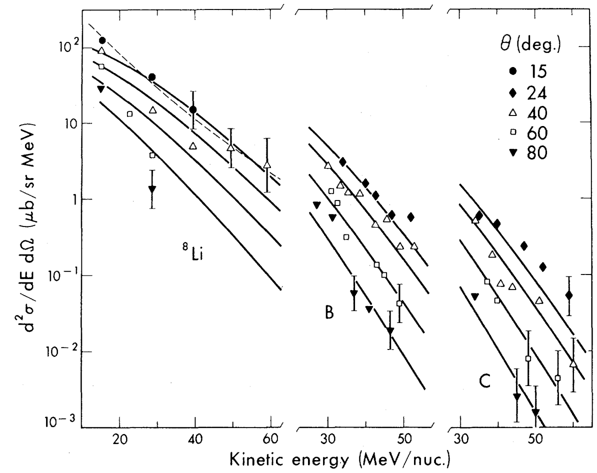

FIG. 2. Complex nuclei produced in irradiation of uranium by ^{20}Ne nuclei at 400 MeV/nucleon. Solid lines are calculated from Eq. (1); dashed line is calculated from Eq. (2).

came to rest at various depths in the stacks from the direction of the target. All sheets were given an ultraviolet irradiation and etched in NaOH solution, then scanned by an ammonia method. (For techniques, see Fleischer, Price, and Walker.[3]) Tracks of nuclei with $5 \leq Z \leq 9$ were identified with a charge resolution $\Delta Z \approx \pm 0.3$. By microscopic scanning for hammer tracks (from the reaction $^8\text{Li} \to {}^8\text{Be} \to 2\,{}^4\text{He}$) we were able also to determine spectra for ^{8}Li. Error bars in Fig. 2 are indicated in cases for which the error due to counting statistics was larger than the systematic error. To avoid clutter, error bars are not indicated in Fig. 1. The point at highest energy for each angle and species has the largest counting error, sometimes as much as a factor of 2. The major systematic error, due to uncertainty in the efficiency of detecting tracks of nuclei with $5 \leq Z \leq 9$ with the ammonia method, was about $\pm 20\%$ for the data in Fig. 1 and $\pm 30\%$ for the data in Fig. 2.

With appropriate use of Lorentz transformations and a least-squares-fitting routing, we have found that our data are consistent with the following statements: (1) The complex nuclei are emitted approximately isotropically from a source moving in the beam direction with a weighted average velocity $\langle\beta_0\rangle = 0.085 \pm 0.006$ for the Ar + Au reaction and $\langle\beta_0\rangle = 0.076 \pm 0.017$ for the Ne + U reaction. (2) In the energy interval studied, the invariant cross section is consistent with either of the following expressions:

$$\frac{1}{P}\frac{d^2\sigma(Z,E)}{dE\,d\Omega} = K_1(Z,A)\exp\left[-\frac{E'}{\tau(Z)}\right], \qquad (1)$$

or

$$\frac{1}{P}\frac{d^2\sigma(Z,E)}{dE\,d\Omega} = K_2(Z,A)\exp\left[-\frac{P'}{P_0(Z)}\right], \qquad (2)$$

where E and P are lab kinetic energy and momentum and E' and P' are the same quantities referred to the moving frame. In the approximation $P = (2ME)^{1/2}$ (valid in the range of energies reported here), Eq. (1) is a Maxwellian distribution. Because a thermal distribution naturally leads to isotropic emission, most of our discussion focuses on Eq. (1). Table I lists the least-squares best-fit values of K_1, τ, and β_0 for each species (typical 90%-confidence-level limits are $\Delta\beta_0 \approx 0.01$, $\Delta\tau \approx 8$ MeV) and the weighted average $\langle\tau\rangle$ and $\langle\beta_0\rangle$ for each reaction. The solid curves in Fig. 1 and 2 were calculated using, for simplicity, the weighted average values $\langle\beta_0\rangle = 0.085$, $\langle\tau\rangle = 65$ MeV for the Ar + Au reaction (with $K_1 = 0.26$, 0.10, 0.06, 0.024, 0.031, and 0.013 for ^{8}Li, B, C, N, O, and F, respectively), and $\langle\beta_0\rangle = 0.076$, $\langle\tau\rangle = 52$ MeV for the Ne + U reaction (with $K_1 = 0.16$, 0.06, and 0.026 for ^{8}Li, B, and C, respectively).

With the same values of β_0 and values of $P_0 \approx 300$ MeV/c for the Ar + Au reaction and $P_0 \approx 240$

TABLE I. Average velocities and thermal parameters of emitting sources.

	400-MeV/N Ne+U			500-MeV/N Ar+Au		
	$\langle\beta_0\rangle$	$\langle\tau\rangle$ (MeV)	K_1 (μb/sr MeV^2/c)	$\langle\beta_0\rangle$	$\langle\tau\rangle$ (MeV)	K_1 (μb/sr MeV^2/c)
^{8}Li [a]	0.060	37	0.51	0.059	56	0.35
B [a]	0.091	62	0.02	0.070	61	0.16
C [a]	0.087	61	0.008	0.087	61	0.085
N [a]				0.100	61	0.028
O [a]				0.082	69	0.023
F [a]				0.087	74	0.0059
Weighted average	0.076	52	...	0.085	65	...
Calc. for fireball [b]	0.27	49	...	0.38	63	...
Calc. for target explosion	0.08	14	...	0.18	40	...

[a] Inferred from angular and energy distributions of fragments.
[b] Ref. 6.

MeV/c for the Ne+U reaction, the fits to Eq. (2) are as good as the fits using Eq. (1). The dashed curve in Fig. 2 shows the fit to the ^{8}Li data at 15°. The predictions of Eqs. (1) and (2) diverge, of course, at both low and high energies, and future measurements over a wider energy interval should allow at least one of these two expressions to be rejected as inadequate.

Figure 3 shows values of β_0 calculated for several values of β', the velocity of the emitted particle in the moving frame. Included at the bottom of Fig. 3 is an analysis of the data for boron and carbon fragments emitted in the reaction ^{12}C+Au (Ref. 1). The earliest observations[4] of complex nuclei in high-energy nucleus-nucleus reactions showed that at very low kinetic energies ($\beta' \approx 0.05$) the distributions were approximately isotropic in a frame with a very low $\langle\beta_0\rangle \approx 0.007$. This result, together with the trends in Fig. 3, suggests that β_0 increases with β', i.e., fragments of highest energies tend to be emitted from sources moving the fastest. The inclusion of an increase of β_0 with β' in the calculations would alter the values of K_1 and τ listed in Table I but would not alter the conclusion that complex nuclei with a spectrum of kinetic energies extending beyond 60 MeV/nucleon are emitted from a source with very low translational kinetic energy (1–3 MeV/nucleon).

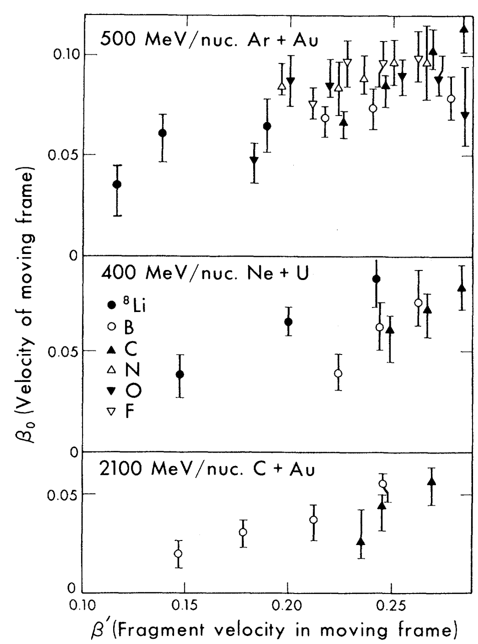

FIG. 3. Velocity of frame in which the angular distribution, evaluated in that frame, is most nearly isotropic. The data for the C+Au reaction are taken from Ref. 1.

If the parameter τ in Eq. (1) is interpreted as the temperature of an emitting source, then the combination of high τ and low β_0 required to fit the spectra of complex nuclei is incompatible with present macroscopic models of nucleus-nucleus collisions and energy-momentum conservation. In these models it has been proposed that projectile and target nuclei make clean cuts through each other and that the "spectator" pieces from the collision give rise to the projectile fragments and the spallation residues.[5] The nucleons mutually swept out from the projectile and target (called the "participants") in the primary interaction are assumed to form a quasiequilibrated nuclear fireball that decays as an ideal gas, giving rise to nucleons[6] and nuclei[2] of intermediate velocity. The next to last line in Table I gives β_0 and τ calculated for the fireball generated in a collision with the most probable impact parameter. Clearly, β_0 is seriously overestimated, nor does consideration of other impact parameters bring about agreement. The last line shows that, if it is assumed that the entire target absorbs the momentum of the entire projectile (denoted "target explosion" in Ref. 6) both β_0 and τ are reduced and τ becomes much too low. Target evaporation would give a very low β_0 and far too low a τ. The introduction of "fractional transparency"[6] would lead to two fireballs, neither of which can be made to fit both β_0 and τ. Regardless of impact parameter, present models give either a low β_0 and low τ or a high β_0 and high τ but cannot give a low β_0 and high τ. Despite the large error bars associated with individual data points, the extensive energy and angular intervals covered result in sufficiently small uncertainties in β_0 and τ that the conclusion seems inescapable: Contributions from nuclear fireballs or other thermal sources to the energetic complex nuclei are negligible compared with contributions from nonthermal mechanisms.

The fireball model was designed to explain the yields of the most abundant charged products —the protons—and it accounts reasonably well for the overall features of proton spectra at energies greater than ~80 MeV, for nucleus-nucleus reactions at a few hundred MeV per nucleon. How well does it account for particles with $A > 1$? For the 400-MeV/nucleon Ne + U reaction, we have calculated what fraction of the various products with $A = 1$ up to 12 could come from a fast fireball with weighted average $\langle\beta_0\rangle = 0.27$ and $\langle\tau\rangle = 49$ MeV. We used a least-squares-fitting routine, assumed one source to be the fast fireball with the total yield a free parameter, and assumed a second source with three parameters —total yield, speed β_2, and apparent temperature τ_2. The results are shown in Table II. Note that the fraction of particles that might come from the fast fireball decreases rapidly with A. Note also that the speed of the second source is always low and its apparent temperature high, *for the light nuclei as well as for the complex nuclei.* The combinations of β_2 and τ_2 in Table II are incompatible with residual target evaporation, target explosion, or thermal emission from a fireball whose properties are consistent with energy-momentum conservation.

We do not wish to reject the fireball model but rather to point out that another source, probably nonthermal in nature, as suggested by earlier data,[4] must contribute a fraction of particles that rapidly increases with their complexity until it becomes dominant for $Z \gtrsim 2$.

TABLE II. Two-source model for 400-MeV/N Ne + U reaction. Source 1: fireball, $\beta_0 = 0.27$, $\tau = 49$ MeV; source 2: a thermal source at β_2, τ_2.

A_Z	β_2	τ_2 (MeV)	Rel. yield 1/(1+2)
^{1}H [a,b]	0.078	26	0.53
^{2}H [b]	0.083	26	0.24
^{3}H [b]	0.079	24	0.13
^{3}He [b]	0.15	49	0.11
^{4}He [b]	0.10	36	0.12
^{8}Li	0.052	35	0.041
B	0.073	56	0.017
C	0.080	62	0.016

[a] At $E \leq 80$ MeV.
[b] Data from Ref. 2.

In nonequilibrium emission from a large system such as the entire target, recoiling with low β_0, it is easier to satisfy relativistic kinematics than when dealing with an equilibrated system, because the internal energy does not have to reach the value $\frac{3}{2}\tau$ per nucleon. Various cooperative or nonthermal processes should be considered. Among these are compressional wave phenomena, multiple scattering by virtual clusters within the nucleus,[7] and the release of pre-existing clusters with very large virtual momenta inside the nucleus.[8] The latter two lead to an exponential *momentum* distribution.

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†John Simon Guggenheim Fellow 1976–1977.

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Search for Particle-Bound Polyneutron Systems

Anthony Turkevich, James R. Cadieux, John Warren, Thanasis Economou, Jerome La Rosa, and H. Roland Heydegger
The Enrico Fermi Institute and Chemistry Department, The University of Chicago, Chicago, Illinois 60637, and Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87545, and Department of Physics, Lakehead University, Thunder Bay, Ontario P7B 5E1, Canada, and Department of Chemistry, Purdue University, Calumet Campus, Hammond, Indiana 46323
(Received 17 March 1977)

A search for particle-bound polyneutron systems (^6n–^{12}n) produced in ~ 700-MeV proton interactions with uranium has yielded negative results. A radiochemical technique was used. The limits on production cross section—10^{-3} to 10^{-5} μb—are many orders of magnitude lower than previous limits at comparable energies, are lower than predictions based on extrapolation of yields of other neutron-rich species, and are in contrast to the positive results reported recently from work with 24-GeV protons on tungsten.

At various times there have been speculations about the existence of particle-stable polyneutron systems, ^xn. The stability of such systems with $x \leq 5$ appears to be ruled out by reasonably direct theoretical arguments, and several experimental searches for such entities have yielded negative results.[1] The theoretical case against heavier polyneutron systems being particle-stable is less convincing, although extrapolations of data on known nuclei[2] and standard theoretical treatments[3] predict no "nuclear" binding, at least until $x > 100$. However, these considerations involve appreciable extrapolations from situations where they have been tested, and their sensitivity to any many-body forces is uncertain. Moreover, very recently, Detraz[4] has reported evidence for the production of polyneutron species in the 24-GeV bombardment of tungsten. It is, therefore, worth reporting on a sensitive experimental search for such heavy polyneutron systems produced under conditions that are known to yield very neutron-rich nuclear species.

Several targets bombarded with 800-MeV protons were investigated as production sources for polyneutron systems. The results reported here are from the one leading to the lowest upper limits.

Heavy elements such as Pb and U are known to produce very neutron-rich nuclides when bombarded with high-energy protons. For example, ^{8}He, ^{11}Li, and ^{17}B have been produced by ~5-GeV protons on uranium[5] with cross sections of about 4200, 200, and 5 μb, respectively. In the present experiment 90 g cm^{-2} of ^{238}U was bombarded for about 10 h with almost 5 μA of 800 MeV protons at the Clinton P. Anderson Meson Physics Facility (LAMPF), leading to 2.8×10^{17} primary-proton–uranium interactions. The average energy of the protons was 700 MeV. In the experimental arrangement, any neutral particles produced more or less isotropically should have escaped the uranium target without significant attenuation and entered the detector material. The mass of the uranium as well as the $\frac{3}{8}$-in. aluminum walls would have stopped most charged particles.

A radiochemical method was used to detect the presence of bound polyneutron systems. This method depends on the nuclear transformations:

$$
\begin{array}{ccc}
{}^{208}\mathrm{Pb} + {}^{x}n\{{}^{208+x}\mathrm{Pb}\}^{*} \to (x-4)n + & & \underline{{}^{212}\mathrm{Pb}} \\
 & & \beta^{-}\downarrow\ 10.6\ \mathrm{h} \\
 & & {}^{212}\mathrm{Bi} \\
 & & \beta^{-}\downarrow\ 60.6\ \mathrm{m} \\
{}^{208}\mathrm{Pb} & \xleftarrow[\text{short}]{\alpha} & {}^{212}\mathrm{Po}\,.
\end{array}
$$

The conversion of ^{208}Pb to ^{212}Pb is an indicator of