Mass Dependence of Light-Nucleus Production in Ultrarelativistic Heavy-Ion Collisions

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Light nuclei can be produced in the central reaction zone via coalescence in relativistic heavy-ion collisions. Experiment 864 at BNL has measured the production of ten light nuclei with nuclear number $A = 1$ to $A = 7$ at rapidity $y \simeq 1.9$ and $p_T/A \leq 300$ MeV$/c$. Data were taken with a Au beam of momentum of 11.5A GeV$/c$ on a Pb or Pt target with different experimental settings. The invariant yields show a striking exponential dependence on nuclear number with a penalty factor of about 50 per additional nucleon. Detailed analysis reveals that the production may depend on the spin factor of the nucleus and the nuclear binding energy as well.

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Relativistic heavy ion collisions may create high energy density and high baryon density in the reaction zone. Therefore, they are considered to be the best laboratory environment to create novel objects or states such as the quark-gluon plasma [1]. Light nuclei can be produced by the coalescence of created or stopped nucleons [2]. Since the probability of coalescence of a particular nuclear system (d, ^{3}He, etc.) depends on the properties of the hadronic system formed as a result of the collision, the study of the coalescence process is useful in elucidating those properties. For example, in a coalescence model, the coalescence probability depends on the temperature, baryon chemical potential (essentially the baryon density), and the size of the system, as well as the statistical weight of the coalesced nucleus [3]. A thermal model [4] does not use details of cluster creation. However, the dependence of the production on the system configuration is very similar to the coalescence model. The data presented in this paper show evidence that the probability may also depend on the binding energy of the coalesced nucleus. Systematic study of the production of light nuclei is limited by their low production rates in relativistic heavy ion collisions. E864 is the only experiment which is able to measure the production of charged nuclei with $A > 4$ produced in the central reaction zone. However, the nature of the coalescence process tells us that the higher the baryon number, the more sensitive the production rate is to the system's configuration.

In this Letter, the production of protons, neutrons, deuterons, ^{3}He, tritons, ^{4}He, ^{6}He, ^{6}Li, ^{7}Li, and ^{7}Be around rapidity $y \simeq 1.9$ and transverse momentum of $p_T/A \leq 300$ MeV$/c$ in 10% most central Au + Pt(Pb) collisions measured by E864 [5] at Brookhaven National Laboratory is presented. These measurements have significant impact on the strange quark matter [6] search by several experiments in relativistic heavy ion collisions. They also provide information about the thermal equilibrium of the system and the detailed process of coalescence.

E864 [5] at BNL is an open geometry, high data rate apparatus designed to search for novel objects such as strange quark matter. It is a fixed-target experiment at the AGS with incident Au beam momentum of 11.5 GeV$/c$ per nucleon. We can have two independent mass measurements with the E864 apparatus: the tracking system and the hadronic calorimeter. The requirement that the two measurements agree provides excellent particle identification and background rejection. The tracking system has two dipole analyzing magnets followed by three hodoscope planes and two straw stations. It measures momentum, charge, and velocity (β) of charged particles with a mass resolution of few percents in the region of interest. Charge misidentification is less than 1 in 10^8 due to three redundant measurements of energy loss in the hodoscopes. There is an additional mass measurement from the hadronic calorimeter [7] which has good energy ($\Delta E/\sqrt{E} = 0.344/\sqrt{E} + 0.035$) and time ($\sigma_t \simeq 400$ ps) resolutions. A vacuum tank along the beam line reduces the background from beam particles interacting with air. The total length of the apparatus is about 28 m.

The trigger consists of good beam definition, a multiplicity requirement [8], and an optional level II high mass trigger—the late-energy trigger (LET) [9]. The LET utilizes the energy and time-of-flight measurements from the calorimeter. Only the 10% most central collisions were collected for the data presented here. The data are from four different experimental settings optimized for the different physics topics. Proton, deuteron, ^{3}He, and triton measurements are from the 1995 run with the "+0.45 T" field setting on the magnets [10] and with a Pb target of 5% interaction length for Au nuclei. Neutron data are from the 1995 run with the highest field setting of "+1.5 T" (5% Pb target) [11] while the rest of the data are from the 1996 run at the "+1.5 T" field setting with the high mass level II trigger and Pt target of 60% interaction length (physical thickness of 1.5 cm) mainly for the strange quark matter search [12] with the exception that the ^{7}Be and ^{7}Li measurements were from the combination of "−0.75 T" and "+1.5 T" field settings taken in the 1996 run. Because of the open geometry, there is sufficient overlap from different settings for consistency checks [10,12–14].

Because of E864's large acceptance, we are able to divide each measurement into several rapidity (y) and transverse momentum (p_T) bins. At $y \simeq 1.9$ and $p_T/A \leq 300$ MeV$/c$, the acceptance is about 20% for most of the light nuclei. It is in this momentum range where we can compare yields of the different species. In other bins, we do not have acceptance for all the light nuclei detected. Interesting and more detailed aspects of the rapidity and transverse momentum distribution of the produced light nuclei will be presented in other papers [13].

For charged nuclei with $A \leq 3$, the production is relatively high so that the LET trigger is not required and the analysis does not use the hadronic calorimeter. The calorimeter is the only significant detector for the neutron measurement where the tracking detectors serve as tools to calibrate the system and to reject the charged particles which deposit energy in the calorimeter. For nuclei ($A \geq 4$) with low production rate, the LET was required to select those events with high mass candidates. The LET rejects those events without any high mass candidates and achieves a rejection factor of about 70 while maintaining good efficiency for high mass states ($\simeq$50% for ^{4}He and $\gtrsim$85% for $A \geq 5$).

Invariant yields are calculated and presented in terms of $d^2N/(2\pi p_T dp_T dy)$ in Table I. The number of particles (N) is taken from the mass distributions in each rapidity and p_T bin with background subtracted. The background level is about 10% or less in most of the bins. Acceptance and efficiency corrections using either simulation or data analysis are applied with the associated systematic and statistical errors. The errors of the measurements of proton, neutron, deuteron, and ^{3}He are on the order of 10%. The rest of the measurements have larger errors varying from 20% (α, ^{6}He) to 45% (^{6}Li, ^{7}Li, ^{7}Be) due to uncertainty in the LET trigger efficiency ($\simeq$10%), low statistics (up to 40%) and high background level from lower mass nuclei (up to 20%). Target absorption of the produced particles is negligible for the 5% Pb target and about 8% for the 60% Pt target. The total systematic error for these measurements varies from a few percent to about 25%.

Figure 1 shows the invariant yield as a function of nuclear number A for stable or metastable particle with $A = 1$ to $A = 7$. The rapidity binning is $\Delta y = 0.2$ with the exception of $\Delta y = 0.6$ for ^{7}Li. p_T binning is $\Delta p_T = 100$ MeV (100–200 MeV) for $A = 1$ to 3, 250 MeV (500–750 MeV) for ^{4}He, 500 MeV (500 MeV–1 GeV) for ^{6}He and ^{6}Li, and 2 GeV (0–2 GeV, acceptance peaks at 750 MeV) for ^{7}Li and ^{7}Be. These bin sizes keep $p_T/A \leq 300$ MeV. The invariant yields span almost 10 orders of magnitude with striking exponential behavior.

A fit to the A dependence of the invariant yields in this rapidity bin results in a penalty factor of about 50 (48 ± 3, $\chi^2/8 = 4.9$) for each additional nucleon to the nuclear cluster. This penalty factor is much higher than the penalty factor in the system with lower beam energy at the BEVALAC [15,16]. The consequence is that it is much harder to form high mass objects by coalescence, such as strange quark matter.

In a statistical approach to the formation of light nuclei, the yield is proportional to the spin factor $(2J + 1)$ [2–4,15,17]. One can further analyze the deviations of the invariant yields from exponential behavior (Fig. 2A). The measured ratios of proton to neutron, ^{3}He to triton, ^{6}Li to ^{6}He, and their corresponding spin factors strongly indicate that the production rate is proportional to the spin factor $(2J + 1)$ of the produced particle [10–13]. Therefore, it is reasonable to include this spin factor in the production rate, which is consistent with most of the models [2–4,15,17]. Figure 2B shows the spin corrected deviations (from exponential behavior), which still have significant deviations. We note, however, that the ratios for $A = 6$ states with spin factors differing by a factor of 3 are brought into agreement with each other by the spin factor correction [12,13]. The spin correction factor

TABLE I. Invariant yields of light nuclei production at $y = 1.9$ and $p_T/A \leq 300$ MeV/c. The bin size in y is $\Delta y = 0.2$. Invariant yields are calculated in terms of $d^2N/(2\pi p_T dp_T dy)$ in units of GeV$^{-2}c^2$. See details in text.

Species	p	n	d	t	^{3}He
Yield	29.0	25.8	0.567	1.04×10^{-2}	9.65×10^{-3}
[(GeV/c)$^{-2}$]	± 3.2	± 1.7	± 0.034	$\pm 6.6 \times 10^{-4}$	$\pm 3.3 \times 10^{-3}$
Species	^{4}He	^{6}He	^{6}Li	^{7}Li	^{7}Be
Yield	2.55×10^{-4}	5.2×10^{-8}	2.1×10^{-7}	0.92×10^{-8}	1.3×10^{-8}
[(GeV/c)$^{-2}$]	$\pm 6.7 \times 10^{-5}$	$\pm 1.2 \times 10^{-8}$	$\pm 7.9 \times 10^{-8}$	$\pm 4.0 \times 10^{-9}$	$(+3.5 - 2.5) \times 10^{-9}$

is taken as $(2J + 1)/(2 \times \frac{1}{2} + 1)$ with a normalization to the nucleon spin factor of 2.

When the deviation after spin factor correction is plotted as a function of binding energy per baryon as shown in Fig. 3, we can fit the dependence with an exponential function of an inverse slope of $T_s = 5.9 \pm 1.1$ MeV when the A dependence of $(2J + 1)/2 \times 26/48^{A-1}$ is applied. The small difference (n to p ratio of about 1.2 ± 0.1) between the abundances of neutron and proton at freeze-out [10,11,13] is corrected for in the analysis shown in Fig. 3. If the total binding energy [17] instead of the binding energy per baryon is used, the inverse slope is about $T_s \simeq 36$ MeV.

From the measurements of light nuclei production near midrapidity (at $y \simeq 1.9$, where $y_{\mathrm{CM}} \simeq 1.6$) with low transverse momentum, a penalty factor of about 50 for each additional nucleon is found in the invariant yield. Although the total production rate comes from the integration of the whole phase space which might differ from the measured invariant yield (due to flow, etc.), we do not expect the ratios of different particle species between total production and the rapidity and p_T range we cover to be different by orders of magnitude. In fact, if we use the parametrization of the correction factor from [3], the penalty factor is estimated to be between 39 and 72. Therefore, the penalty factor can be applied to estimate the production rates of heavy clusters. Because of the small elastic structure function of light nuclei at large momentum transfer [18], the possibility of light nuclei at $1.0 < y < 2.2$ coming from projectile or target is small compared to the observed production rates.

Naive comparison with theoretical estimates of chemical potential (μ_N) and temperature (T) at freeze-out from low mass hadronic spectra [4] will show us whether the light nuclei might have different μ_N and T at hadronic freeze-out. If we use $\mu_N = 540$ MeV and $T = 120$ MeV [4], we get a penalty factor of $\exp[(m_N - \mu_N)/T] \simeq 28$. A kinetic freeze-out and radial flow analysis shows a higher penalty factor of about 75 with $\mu_N = 536$ MeV and $T \simeq 93$ MeV [3].

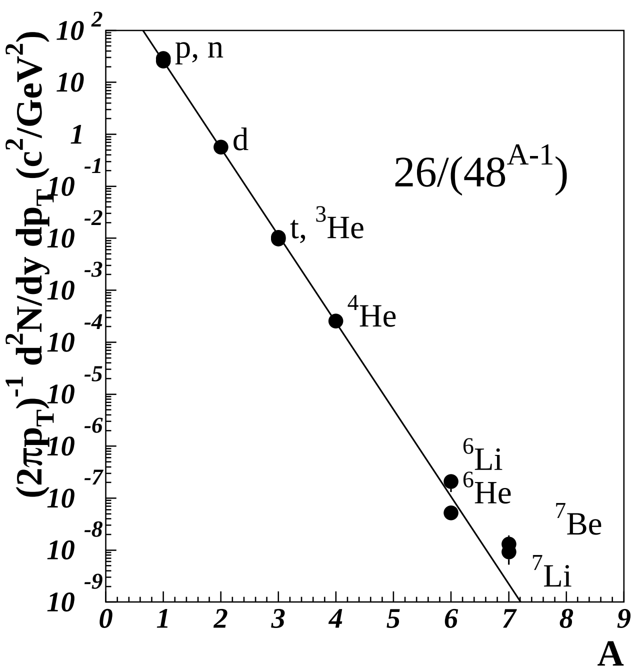

FIG. 1. Invariant yield as a function of nuclear number A. The bin size in rapidity is 0.2 (0.6 for ^{7}Li). $p_T/A \leq 300$ MeV. The J^P's of p, n, d, ^{3}He, t, ^{4}He, ^{6}He, ^{6}Li, ^{7}Li, and ^{7}Be are $\frac{1}{2}^+$, $\frac{1}{2}^+$, 1^+, $\frac{1}{2}^+$, $\frac{1}{2}^+$, 0^+,0^+, 1^+, $\frac{3}{2}^-$, and $\frac{3}{2}^-$, respectively. The line is a fit to the data with $26/(48^{A-1})$.

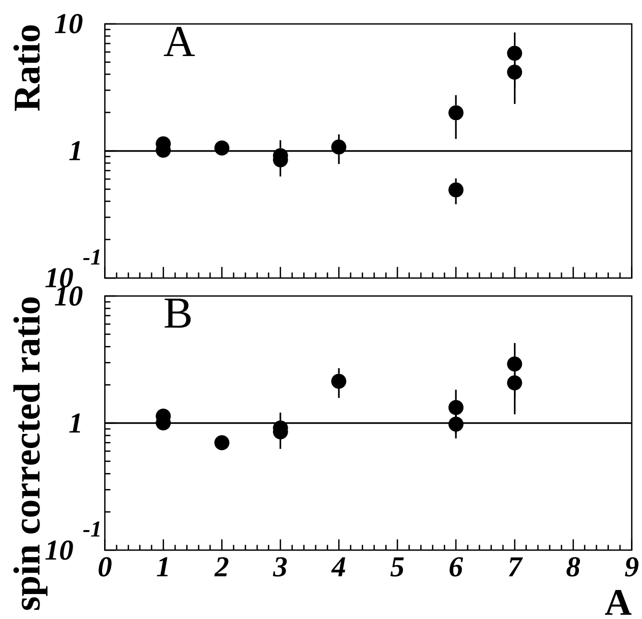

FIG. 2. Ratio of the invariant yield to the exponential function vs nuclear number A with and without spin factor. The top panel (A) is the ratio and the bottom panel (B) is the ratio with spin correction. See text for details.

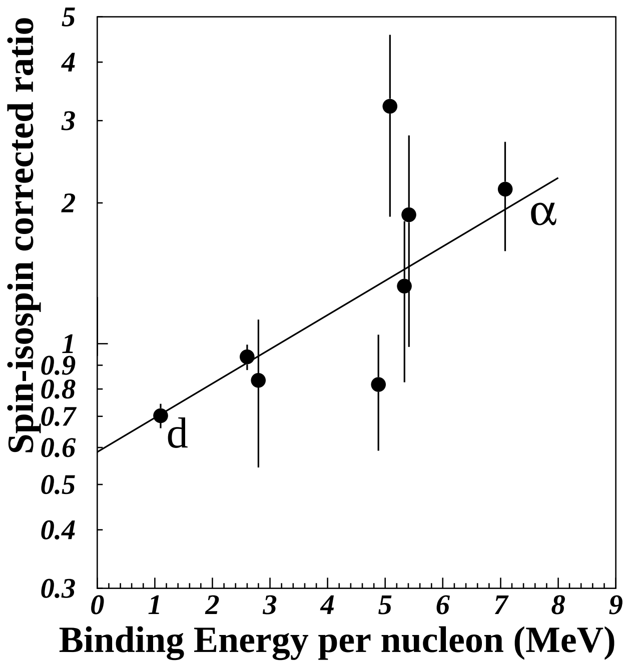

FIG. 3. Ratio of the spin-isospin-factor-corrected invariant yield to the exponential function exhibits exponential dependence on the binding energy per nucleon. The isospin abundance is $(n/p) = 1.2$. Alphas have the largest binding energy per nucleon and therefore have the highest production rate deviation from the global exponential behavior. Neutrons and protons are not in this plot. Binding energies are calculated according to the mass difference between the nucleus and its constituent nucleons. See text for details.

The dependence of production rate on binding energy per baryon shows the sensitivity of our data and cannot be explained by the coalescence model or the thermal model with the simple $\exp[-B/T]$, where $T \simeq 100$ MeV and B is the total binding energy [17]. One possible explanation is that the production rate might depend on the size of the produced object and therefore depend on its binding energy. It is also possible that there exists some subtle final state interaction which depends on the size or the binding energy. For example, collisions with sufficient energy to break up the nuclei can occur down to surviving temperatures which are comparable with the binding energy [19].

In summary, E864 measures the invariant yields of light nuclei production of protons, neutrons, deuterons, ^{3}He, triton, ^{4}He, ^{6}Li, ^{6}He, ^{7}Li, and ^{7}Be near y_{CM} and $p_T \simeq 0$. A striking exponential behavior of light nucleus production as a function of nuclear number is found. The penalty factor, extracted from the light nuclei production rates, for an additional nucleon in the nuclear cluster is about 50. Detailed analysis reveals that the invariant yield may also depend on the spin factor and the binding energy of the produced nucleus.

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