Mass dependence of light nucleus production in ultrarelativistic heavy ion collisions

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(March 30, 2022)

Light nuclei can be produced in the central reaction zone via coalescence in relativistic heavy ion collisions. E864 at BNL has measured the production of ten light nuclei with nuclear number of A = 1 to A = 7 at rapidity y ≃ 1.9 and pT/A ≤ 300 MeV/c. Data were taken with a Au beam of momentum of 11.5 A 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.

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. At the AGS energies (√s ≃ 4.8 AGeV), the baryon stopping is high, which means that the baryon density near center-of-mass rapidity is quite large compared to the much higher beam energy at the SPS (√s ≃ 17 AGeV) or at the RHIC (√s ≃ 200 AGeV). Light nuclei can be produced by the coalescence of created or stopped nucleons. Since the probability of coalescence of a particular nuclear system (d, 3He, 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. A thermal model 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 shows 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, 3He, tritons, 4He, 6He, 6Li, 7Li and 7Be around rapidity y ≃ 1.9 and transverse momentum of pT/A ≤ 300 MeV/c in 10% most central Au+Pb collisions measured by E864 at BNL is presented. These measurements have significant impact on the strange quark matter 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 at Brookhaven National Laboratory 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 (M1 and M2) followed by three hodoscope planes (H1, H2 and H3). There are two straw stations (S2 and S3), each with three close-packed double planes. Each scintillating hodoscope plane has 206 vertical slats, and there are 960 and 1920 straw tubes in each S2 and S3 straw plane respectively. The tracking system measures momentum, charge and velocity \((\beta)\) of charged particles with a mass resolution of few percents in the region of interest. Charge misidentification is less than 1 in \(10^6\) due to three redundant measurements of energy loss in the hodoscopes. There is an additional mass measurement from the hadronic calorimeter which has good energy \((\Delta E/\sqrt{E} = 0.344/\sqrt{E} + 0.035)\) and time \((\sigma_t \approx 400\text{ps})\) resolutions. It is made of 754 towers of scintillating fiber-embedded lead. The containment of a hadronic shower is about 50\% in the peak tower and about 90\% in the \(3 \times 3\) array around the peak tower. This allows sufficient quality requirements of the shower cluster and provides good neutron measurements. 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 meters.

The trigger consists of good beam definition, a multiplicity requirement and an optional level II high mass trigger – the Late-Energy Trigger (LET). 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 \(”+0.45\text{T}”\) field setting on M1 and M2 magnets 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 \(”+1.5\text{T}”\) (5\% Pb target) while the rest of the data are from the 1996 run at the \(”+1.5\text{T}”\) field setting with the high mass level II trigger and Pt target of 60\% interaction length (physical thickness of 1.5cm) mainly for the strange quark matter search with the exception that the \(^7\)Be and \(^7\)Li measurements were from the combination of \(”+1.5\text{T}”\) and \(”+1.5\text{T}”\) field settings taken in the 1996 run. Due to the open geometry, there is sufficient overlap from different settings for consistency checks.

Because of E864’s large acceptance, we are able to divide each measurement into several rapidity \((y)\) and transverse momentum \((p_T)\) bins. At \(y \approx 1.9\) and \(p_T/A \leq 300\text{MeV/c}\), 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.

For charged nuclei with \(A \leq 3\), the production rates are 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 high mass 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 (\(\approx 50\%\) for \(^4\)He and \(\approx 85\%\) for \(A \geq 5\)).

Invariant yields are calculated and presented in terms of \(d^2N/(2\pi p_T dp_T dy)\) in units of \(\text{GeV}^{-2}\text{c}^2\) as shown in Table I. The number of particles \((N)\) are 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\% \((\alpha, ^6\text{He})\) to 45\% \((^6\text{Li}, ^7\text{Li}, ^7\text{Be})\) due to uncertainty in the LET trigger efficiency (\(\approx 10\%\)), 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 \(\Delta p_T = 100\text{MeV} (100\text{MeV}-200\text{MeV})\) for \(A = 1\) to \(3, 250\text{MeV} (500\text{MeV}-750\text{MeV})\) for \(^4\)He, \(500\text{MeV} (500\text{MeV}-1\text{GeV})\) for \(^6\)He and \(^8\)Li, and \(2\text{GeV} (0-2\text{GeV})\) acceptance peaks at \(750\text{MeV}\) for \(^7\)Li and \(^7\)Be. These bin sizes keep \(p_T/A \leq 300\text{MeV}\). The invariant yields span almost ten orders of magnitudes 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 \((48 \pm 3, \chi^2/8 = 4.9)\) 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 \(\text{[14,18]}\). 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 \((2J+1)\). One can go one step further to analyze the deviations of the invariant yields from the exponential behavior (figure 2A). The measured ratios of proton to neutron, \(^3\)He to triton, \(^6\)Li to \(^8\)He and their corresponding spin factors strongly indicate that the production rate is proportional to the spin factor \((2J+1)\) of the produced particle \(\text{[9,11,13]}\). Therefore, it is probably reasonable to
include this spin factor in the production rate, which is consistent with most of the models [4, 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 [13]. The spin correction factor is taken as \((2J + 1)/(2 \times 3 + 1)\) 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 Figure 3, we can fit the dependence with an exponential function of an inverse slope of \(T_s = 5.9 \pm 1.1 \text{MeV}\) when the A dependence of \((2J + 1)/2 \times 6/48A^{-1}\) 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 [13, 14] is corrected for in the analysis shown in Figure 3. If the total binding energy [3] instead of the binding energy per baryon is used, the inverse slope is about \(T_s \approx 36 \text{MeV}\).

From the measurements of light nuclei production near midrapidity (at \(y \approx 1.9\), where \(y_{CM} \approx 1.6\)) 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 [10], 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. Due to the small elastic structure function of light nuclei at large momentum transfer [19], the possibility of light nuclei at 1. \(< y < 2.2\) coming from projectile or target is small compared to the observed production rates.

Naive comparison with theoretical estimates of chemical potential and temperature at freeze-out from low mass hadronic spectra [3] will show us whether the light nuclei might have different chemical potential and temperature at hadronic freeze-out. If we use the chemical potential of \(\mu_N = 540 \text{MeV}\) and temperature of \(T = 120 \text{MeV}\) [3], we get a penalty factor of \(\exp((m_N - \mu_N)/T) \approx 28\). A kinetic freeze-out and radial flow analysis shows a higher penalty factor of about 75 with \(\mu_N = 536 \text{MeV}\) and \(T \approx 93 \text{MeV}\) [14].

The dependence of production rate on binding energy per baryon shows the sensitivity of our data and can not be explained by the coalescence model or the thermal model with the simple \(\exp[-B/T]\) where \(T \approx 100 \text{MeV}\) 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 [20].

In summary, E864 measures the invariant yields of light nuclei production of protons, neutrons, deuterons, \(^3\text{He}\), triton, \(^4\text{He}\), \(^6\text{Li}\), \(^6\text{He}\), \(^7\text{Li}\) and \(^7\text{Be}\) near \(y_{CM}\) and \(p_T \approx 0\). 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.

We gratefully acknowledge the excellent support of the AGS staff. This work was supported in part by grants from the U.S. Department of Energy’s High Energy and Nuclear Physics Divisions, and the U.S. National Science Foundation.

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

\[ \begin{array}{cccccc}
0 & 1 & 2 & 3 & 4 & 5 \\
0 & 9 & 9 & 9 & 9 & 9 \\
\end{array} \]
FIG. 2. Ratio of the invariant yield to the exponential function vs. nuclear number $A$ with and without spin factor. The top panel is the ratio and the bottom panel 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.
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 | $p$ | $n$ | $d$ | $t$ | $^5He$ |
|---------|-----|-----|-----|-----|--------|
| Yield ((GeV/c)$^{-2}$) | $29.0 \pm 3.2$ | $25.8 \pm 1.7$ | $0.567 \pm 0.034$ | $1.04 \times 10^{-2} \pm 6.6 \times 10^{-4}$ | $9.65 \times 10^{-3} \pm 3.3 \times 10^{-3}$ |
| Species | $^4He$ | $^6He$ | $^6Li$ | $^7Li$ | $^7Be$ |
| Yield ((GeV/c)$^{-2}$) | $2.55 \times 10^{-4} \pm 6.7 \times 10^{-5}$ | $5.2 \times 10^{-8} \pm 1.2 \times 10^{-8}$ | $2.1 \times 10^{-7} \pm 7.9 \times 10^{-8}$ | $0.92 \times 10^{-8} \pm 4.0 \times 10^{-9}$ | $(+3.5 - 2.5) \times 10^{-9}$ |