Production of Light (anti-)Nuclei with E864 at the AGS

Zhangbu Xu for the E864 Collaboration
Physics Department, Yale University
CT 06520, USA
E-mail: xzb@hepmail.physics.yale.edu

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 stable light nuclei with nuclear number of \(A = 1\) to \(A = 7\) at rapidity \(y \approx 1.9\) and \(p_T/A \leq 300\) 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 over ten orders of magnitude with a penalty factor of about 50 per additional nucleon. This penalty factor is used to estimate the strange quark matter (strangelet) production in the baryon rich and strangeness enhanced environment. The measurements of the production of antiproton, antideuteron, hypernuclei (\(^3\Lambda H, ^4\Lambda H\)), and strongly unstable nuclear states (\(^4H, ^5Li, ^5Li^*, ^5He\)) are presented as well. A model of local thermal equilibrium with radial flow at the kinetic freeze-out with a temperature of \(T = 112 \pm 10\) MeV, chemical potential of \(\mu_B = 503 \pm 20\) MeV and flow velocity of about \(\sqrt{V^2} \approx 0.5c\) seems to be able to describe the data in the gross scale with the exceptions of the production of antihyperons and hypernuclei. The large antihyperon production and the extra penalty for hypernuclei production are quite surprising.

1. Introduction

Relativistic heavy ion collisions may create high energy density and high baryon density in the reaction zone. Light nuclei can be produced by the recombination of created or stopped nucleons. This recombination process is called coalescence. Coalescence of nuclear clusters can be characterized by the penalty factor for a nucleon added to the nuclear cluster. This idea can be extended to hypernuclei to calculate the strangeness penalty factor. Both baryon and strangeness penalty factor are useful to estimate the production rate of strange quark matter in terms of coalescence or thermal production. 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 (degeneracy) of the coalesced nucleus. The data reported shows evidence that the probability may also depend on the binding energy of the coalesced nucleus at the level of about 6MeV. 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. For example, the inverse slope of the transverse momentum distribution (effective temperature) of “heavy” light nuclei is very sensitive to the density profile and radial flow profile. Production of antinuclei will provide additional information about the equation of state of the system and the state of chemical or kinetic equilibrium.

In this report, the production of $p, n, d, ^3He, t, ^4He, ^6Li, ^7Li$ and $^7Be$ around rapidity $y \simeq 1.9$ and transverse momentum of $p_T/A \lesssim 300 \text{MeV}/c$ in 10% most central Au+Pt(Pb) collisions measured by E864 at BNL is presented together with the production of $\bar{p}, \bar{d}, ^5He, ^5Li, ^4H, ^3Λ$ and the production limits on $^5Li^*$ and $^4ΛH$. 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. The richness of the data in rapidity and centrality will not be discussed here.

2. E864 Apparatus

E864 is an open-geometry and high-data rate apparatus designed to search for new forms of matter. It has large rapidity and transverse momentum coverage. The tracking system consists of 2 dipole magnets for rigidity measurement and particle selection, 3 hodoscopes and 2 straw tube chambers measuring velocity, charge and position. The mass resolution is about 3% in the region of interest in high field settings. There is an additional mass measurement from hadronic calorimeter, which provides good energy and TOF information. These signals are used for a high mass level two trigger as well. More detailed descriptions of the apparatus can be found in other publications.

First, we can measure single-particle spectra of particles, such as $^6He, ^7Li, ^7Be, n, \bar{p}, K^\pm$ and $\pi^\pm$. Because E864 is open-geometry configuration, we have multiple particles in one event. We can also do two-particle correlation to reconstruct the invariant mass of their decay parent. We use event-mixing to subtract the background. Since we do not identify the decay vertex, strong decays and weak decays appear the same technically. Last but not the least, from the large sample of events, we can look for rare products ($\bar{d}$) and search for new forms of matter such as strange quark matter.

3. Results and Discussions

In this section, we will present the results of the single-particle spectra and apply a simplified coalescence model assuming local thermal equilibrium to describe the data in the gross scale. Systematic errors of the temperature
Figure 1: Eighteen hadrons measured by E864. Stable light nuclei are selected from $y = 1.9$ and $p_T/A < 300 $MeV/$c$. $\bar{p}$ is at $y = 1.9$ and $p_T \simeq 0$. $\bar{d}$ is at $y = 1.9$ and $0 < p_T < 1 $GeV/$c$(preliminary). Hypernuclei are from $1.6 < y < 2.6$ with correction of detector’s acceptance(preliminary). Strongly unstable nuclei are from $y = 1.9$ and $p_T \lesssim 2 $GeV/$c$(preliminary). Lines are fits to the data assuming local thermal equilibrium (work in progress). See text for details.

and chemical potential extracted from this model-dependent simplification will be discussed at the end. Radial flow is then studied using the temperature obtained and the inverse slope parameters from the transverse spectra of the $K^+$, p, n, d, $^3He$ and $^4He$(preliminary). Then we will show the results on the production of the hypernuclei and address the strangeness penalty factor. At the end, we will present the limits on strangelet search and discuss the significance of the limits in the context of the coalescence model. Particularly, we will discuss the limits on H-d (bound state of H-dibaryon and deuteron) search.

Figure 2 shows the invariant yields of 18 hadrons we have measured in a selected rapidity ($y$) and transverse momentum ($p_T$) bin. We observe a striking exponential dependence of light nuclei production up to $A = 7$ over ten orders of magnitudes in the invariant yield. Here, we will briefly present the results on $\bar{d}$ production as an example. Invariant yields are calculated and presented in terms of $d^2N/(2\pi p_T dp_T dy)$ in units of $GeV^{-2}c^2$ per central collision. In case of $\bar{d}$, we have a sampled collection of $1.4 \times 10^{10}$ events of 10% most central interactions. A signal of $17.6 \pm 7.5$ in the rapidity range of $1.8 < y < 2.2$ and $4.6 \pm 3.3$ in $1.4 < y < 1.8$ above background is observed. The yields are determined to be $3.5 \pm 1.5(^{stat})^{+0.9}_{-0.5}(sys) \times 10^{-8}GeV^{-2}c^2$ and
3.7 \pm 2.7 (stat)^{+1.4}_{-1.5} (sys) \times 10^{-8} \text{GeV}^{-2}c^2 \text{ respectively.} \quad (11)

These measurements suggest that the coalescence parameters \( B_2 \) and \( B_2' \) are consistent with each other. In this report, we will assume that antinuclei and nuclei have the same temperature \( T \) and chemical potential \( (\mu_B) \) at the kinetic freeze-out. We fit the production of the ten stable light nuclei with an exponential as a function of nuclear (baryon) number. The best fit is \( 26/48A^{-1} \). If we take our \( \bar{p} \) and correct it for the antihyperon feeddown\(^6\) at 98% confidence level (CL)in \( y = 1.9 \) near \( p_T \simeq 0 \), we have the fugacity\(^7\) (Eq.6.6) of \( \lambda^2 = \exp(2\mu_B) = p/\bar{p} = 23.3/0.0038 \). The fugacity can also be obtained from \( d/d \): \( \lambda'^4 = d/d = 0.56/(3.5 \times 10^{-8}) \). The difference between \( \lambda \) and \( \lambda' \) comes from the difference of the isospin abundance or \( n/p \) ratio in a thermal distribution. From our unique measurement of \( n/p = 1.19 \pm 0.08 \), we have \( \lambda' = 1.1 \lambda \). For simplicity, the average fugacity or chemical potential are taken as: \( \lambda_B = \sqrt{\lambda' \lambda} \), and \( \mu_B = (\mu_p + \mu_n)/2 \). In fact, the fugacity from \( p/\bar{p} \) at 98% CL is within the error of that from \( d/d \). If we consider the penalty factor coming from the possibility of the population of the state as in a thermal system and neglect all the other details (flow has built up before the coalescence process and there is not additional momentum redistribution of the cluster after-burner), we have

\[
\exp((m_N - \mu_B)/T) \simeq 48 \quad \text{where} \quad m_N \text{ is the nucleon mass.}
\]

In Figure 3, we plot the three equations above in the phase space of chemical potential and temperature. From the crossing point of the lines from penalty factor and fugacity from \( p/\bar{p} \), we get \( T = 112 \pm 10 MeV \) and \( \mu_B = 503 \pm 20 MeV \) (errors are estimates, work in progress). This is quite close to other measurements\(^8\). In the non-relativistic limit which for the case of nuclei is a good approximation, the kinetic energy can be separated into thermal energy and flow energy as \( T_{eff} = T + \frac{1}{2} mV^2_\perp \) in two-dimension radial flow. Figure 3 is the effective temperature vs. mass up to \( A = 4 \) with \( T = 112 MeV \) at \( m = 0 \). Data of p, n, d, \(^3\)He are at \( y = 2.3 \) where E864 has its best coverage in transverse momentum. For the flow at \( y = 2.3 \), we have to scale \( T \) (\( y = 1.9 \)) and inverse slope parameter of \( A = 4(y = 2.1) \) down by 10% to 20% which was not done in the plot. Therefore, the flow velocity we get probably will be an overestimate.

The fit is \( T_{eff} = 112 + 117 \times A(MeV) \) with a mean velocity \( \sqrt{V^2_\perp} \simeq 0.5 \).

Now we can use the flow and rapidity distribution measured to estimate the systematic error introduced by the model-dependent assumption\(^9\) that the system is in local thermal equilibrium. We can compare the difference between the total yield and the yield in one specific rapidity and momentum. When the parametrization of the correction factor of \( A^x \) from Eq.6.10 is used, the limits of penalty between 39 and 72 are obtained for \( 1 > \chi > -\frac{1}{2} \). If we assume that the temperature distribution in rapidity is a Gaussian with \( \sigma_T = 1.1 \) from our neutron measurements\(^8\) and the effective temperature...
Figure 2: Temperature vs. chemical potential. The square and triangle points are from \cite{10, 7}. \( T = 112 \pm 10 \, \text{MeV}, \mu_B = 503 \pm 20 \, \text{MeV} \) with estimated uncertainty. Errors are not shown. See text for details.

Figure 3: Radial flow from transverse momentum spectra. \( T \) and inverse slope of \( ^4\text{He} \) are at \( y = 1.9 \) and \( y = 2.1 \) respectively which have higher temperature and stronger flow. The curved line is to guide the eye.

scales as \( T_{\text{eff}} \simeq 1.0 + A \) with Boltzmann distribution, then \( T_{\text{eff}} (y) \propto (1.0 + A) \times \exp \left( -\frac{(y - y_{\text{cm}})^2}{2\sigma_T^2} \right) \). We have characterized the yield in rapidity at \( p_T \simeq 0 \) by the concavity \( b/a \) and extrapolated to other nuclei with limited data points. We obtain \( b/a = 0.14, 0.92, 2.8, 2.4, 3.2, 7.7 \) for p,d, \( ^3\text{He}, \, ^t, \, ^4\text{He}, \, ^6\text{He} \) respectively. The penalty factor becomes 25 when we integrate over the transverse momentum and rapidity of \( -0.6 < y - y_{\text{cm}} < 0.6 \) (projectile and target regions are not included to avoid fragmentations, \( dN/dy \propto T_{\text{eff}} (T_{\text{eff}} + m) \sigma_T d^2p_T^2 |_{p_T=0} \)), which should probably be taken as the absolute lower limit because the integration assumes non-correlation between momentum and space in the extrapolation to high \( p_T \) for high mass which is in contradist with the flow phenomenon; in addition, there is indication that the effective temperature does not scale linearly with mass and might saturate at high masses as shown in Figure 3. In conclusion, the penalty factor is about \( 48^{+24}_{-10} \) with uncertainty dominated by model-dependent estimate.

E864 has a sampled collection of about \( 9 \times 10^{10} \) events of 10\% most central interactions for hypernuclei studies. We have analyzed 2/3 of the data and found a \( ^3\Lambda / ^3\text{He} \) signal at 1.8 sigma level above the background after mixed-event background subtraction. The invariant yield is \( 2.6 \pm 1.4 \times 10^{-4} \, \text{GeV}^{-2} \, \text{c}^{2} \) over \( 1.6 < y < 2.6 \) and \( 0 < p_T < 2 \, \text{GeV} / \text{c} \). The strangeness penalty factor is \( \lambda_S = \frac{\Lambda / \text{He}}{^3\text{He} / ^3\Lambda} = 0.036 \pm 0.019 \) with an extra penalty of \( \frac{^3\text{He} / ^3\Lambda}{^3\text{He} / ^3\Lambda} = 0.17 \pm 0.09 \).
For the $^4\Lambda H$, we do not observe any significant signal above background and we set an upper limit at 90% CL of $0.29 \times 10^{-4} \text{GeV}^{-2}c^2$. When the degeneracy of $\Sigma(2J+1) = 4$ is taken into account, we have $\lambda_S = \frac{4}{\Lambda} H/4/4He < 0.032$ which is consistent with the $^3\Lambda H$ case. This extra penalty may come from the quantum mechanical correction. From this, we can write the cluster production as $157/50^{4-1}/30^{[S]}$. The penalty for antimatter coalescing is much larger ($\simeq 10^6$).

We have searched for strangelets (small strange quark matter) with charge of 0, ±1, ±2, ±3 with null result; limits are set between $10^{-9}$ to $10^{-8}$ per central collision over a large mass range. We can discuss the sensitivity in terms of a coalescence mechanism and write the sensitivity as $|A + 0.87|S|< 7.1$ with the newly measured $|\lambda_S|$. For example, we set a limit of $0.9 \times 10^{-7}$ for long-lived H-d state which has been predicted to be produced at a level of $10^{-8} \rightarrow 10^{-7}$ by C. Dover or $157/50^3/30^2 = 1.4 \times 10^{-6}$ from our measurements if it exists.

In summary, we have measured the production of 18 hadrons in relativistic heavy ion collisions at the AGS energies. Information of the colliding system, such as temperature, chemical potential, flow and cluster production rate can be extracted from these measurements. Z. Xu would like to thank Dr. U. Heinz and Dr. J. Stachel for valuable discussions. 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.

References

1. J. L. Nagle et al., Phys. Rev. C 53, 367 (1996), references therein
2. T. A. Armstrong et al., accepted to Nucl. Instrum. Methods A. (1999);
3. R. L. Jaffe, Phys. Rev. Lett. 38, 617E (1977).
4. N. George, et al., 15th Winter Workshop on Nuclear Dynamics, Park City, UT, January 13, 1999(edt. W. Bauer, et al., Kluwer Academic/plenum Publishers);N. George, PhD Thesis, Yale University 1999.
5. Z. Xu, et al., J. Phys. G 25, 403-410 (1999); T. A. Armstrong et al., nucl-ex/9907002; Z. Xu, PhD Thesis, Yale University 1999.
6. T. A. Armstrong et al., nucl-ex/9909001; E. Finch, PhD Thesis, Yale University 1999.
7. R. Scheibl et al., Phys. Rev. C 59, 1585 (1999); H. Dobler, et al., nucl-th/9904013.
8. T. A. Armstrong et al., Phys. Rev. C 59, 2699 (1999).
9. G. Van Buren, et al., QM’99 talk, May 13, Torino, Italy.
10. P. Braun-Munzinger and J. Stachel, J. Phys. G: Nucl. Part. Phys. 21, L17 (1995); P. Braun-Munzinger et al., Phys. Lett. B 344, 43 (1995).
11. S. Batsouli, et al., talk at APS Heavy-Ion Mini-symposium, March 23, 1999. (edited R. Seto, World Scientific Publisher)