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Chapter 48

Light Nuclei Production in Ultra-Relativistic Heavy Ion Collisions



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Abstract We briefly overview the motivations of recent studies of light nuclei production in ultra-relativistic heavy ion collisions: anti-nuclei in space, and search for the critical point of the strongly-interacting matter. Then we focus on a particular recent development—the possible solution of the “snowballs in hell” puzzle—why the nuclei with binding energies of few MeV apparently survive at temperatures of around 155 MeV. Recent simulations within a hydrodynamics + hadronic transport approach, where deuterons are produced and destroyed mainly in $\pi pn \leftrightarrow \pi d$ reactions show that deuterons do not survive. They are rather created and disintegrated with approximately equal rates during certain period of time. Complementing previous publications, we show that these simulations reproduce not only deuteron spectra, but also the deuteron flow v_2 in PbPb collisions at 2.76 TeV.

48.1 Overview: Anti-nuclei in Space and Relation Between Light Nuclei Production and Critical Fluctuations

In the few past years light nuclei production (d , t , ${}^3\text{He}$, ${}^3_\Lambda\text{H}$, ${}^4\text{He}$, and their antiparticles) in ultra-relativistic heavy ion collisions has been actively explored, both theoretically and experimentally. There are at least two major motivations. First, AMS-02

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experiment at the International Space Station [1] has measured anti-nuclei in space [2], possibly including few unpublished events of ${}^3\overline{\text{He}}$ and ${}^4\overline{\text{He}}$. These events may originate from exotic sources such as antimatter clouds in space or dark matter annihilations, and from ordinary sources, such as pp , pA , and AA collisions. Presently the estimates of the ordinary pp background vary by an order of magnitude [3, 4], even though models are calibrated using the same data [5]. This stimulated interest to building more precise models of light nuclei production and obtaining new data to constrain them.

Another reason to study light nuclei is related to the search of the critical point of strongly-interacting matter [6]. A generic feature of this critical point is that in its vicinity spatial fluctuations of the baryon density are expected to increase. Experimentally only momentum space is accessible, therefore spatial fluctuations cannot be measured directly. However, based on a simple coalescence model it was recently suggested, that light nuclei production is sensitive to these fluctuations [7, 8]. In this model the density is separated into average and fluctuating contributions

$$\rho_n(x) = \langle \rho_n \rangle + \delta \rho_n(x) \quad (48.1)$$

$$\rho_p(x) = \langle \rho_p \rangle + \delta \rho_p(x) \quad (48.2)$$

and the triton and deuteron yields are expressed as

$$N_d \approx \frac{3}{2^{1/2}} \left(\frac{2\pi}{mT} \right)^{3/2} \int d^3x \rho_p(x) \rho_n(x) \sim \langle \rho_n \rangle N_p (1 + C_{np}) \quad (48.3)$$

$$N_t \approx \frac{3^{1/2}}{4} \left(\frac{2\pi}{mT} \right)^3 \int d^3x \rho_p(x) \rho_n^2(x) \sim \langle \rho_n \rangle^2 N_p (1 + 2C_{np} + \Delta \rho_n), \quad (48.4)$$

where

$$C_{np} \equiv \langle \delta \rho_n(x) \delta \rho_p(x) \rangle / (\langle \rho_n \rangle \langle \rho_p \rangle) \quad (48.5)$$

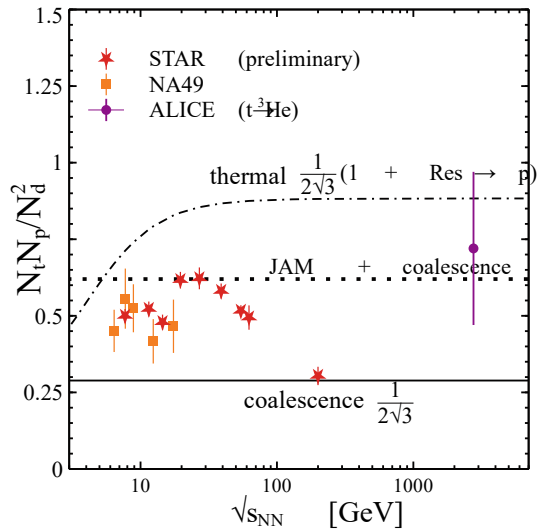
$$\Delta \rho_n \equiv \langle \delta \rho_n(x)^2 \rangle / \langle \rho_n^2 \rangle. \quad (48.6)$$

Here C_{np} represents the spatial correlations between neutrons and protons, and $\Delta \rho_n$ corresponds to the spatial fluctuations of neutron density. Therefore the ratio $N_t N_p / N_d^2$ becomes

$$\frac{N_t N_p}{N_d^2} = \frac{1}{2\sqrt{3}} \frac{1 + 2C_{np} + \Delta \rho_n}{(1 + C_{np})^2} \quad (48.7)$$

Here the factor $\frac{1}{2\sqrt{3}}$ originates from spin degeneracies and masses, $\frac{g_t g_p}{g_d^2} \left(\frac{3m \cdot m}{(2m)^2} \right)^{3/2} = \frac{1}{2\sqrt{3}} \approx 0.29$, and the second factor characterizes spatial correlations and fluctuations. In absence of fluctuations and correlations the ratio $\frac{N_t N_p}{N_d^2}$ is expected to be independent of collision energy, centrality, baryon or isospin content of the system. Therefore a non-flat behaviour of the ratio $N_t N_p / N_d^2$ against collision energy characterizes spatial fluctuations and may help to locate the critical point. The experimentally

Fig. 48.1 Comparison of the $\frac{N_t N_p}{N_d^2}$ ratio in central PbPb or AuAu collisions at midrapidity between data from NA49 [10–12] (squares), STAR [13–15] (stars), and ALICE [16] collaborations (circle) and models (lines): uniform coalescence (solid) [7], thermal (dash-dotted) [17], and JAM hadronic transport with coalescence afterburner [9]



measured $N_t N_p / N_d^2$ ratio indeed exhibits a non-flat behaviour against energy, as shown in Fig. 48.1. However, a theoretical interpretation of this behaviour is currently not possible, because different models of light nuclei production do not agree even without critical point effects. This disagreement can be traced back to the model assumptions. The coalescence model assumes that light nuclei are produced at the late stage of the collision, when all resonances, such as Δ^* and N^* have decayed into nucleons. Then nucleons form light nuclei as described above, resulting in $\frac{N_t N_p}{N_d^2} = \frac{1}{2\sqrt{3}}$. Correlations between protons and neutrons and $\Delta\rho_n$ from thermal fluctuations are neglected. In the thermal model nuclei are formed from nucleons early, at the hadronic chemical freeze-out. After this resonances decay into protons, increasing their amount by a feed-down factor of $(1 + Res \rightarrow p)$, which varies from roughly 1.5 to 3 depending on collision energy. The intermediate case is represented by the JAM + coalescence model [9], where the JAM transport code is run until time 40 fm/c, allowing some resonances to decay into protons and neutrons and then coalescing nucleons that lie close in the phase space. Interestingly, the ratio $N_t N_p / N_d^2$ in this model is almost independent on collision energy, even though it takes into account correlations between protons and neutrons, as well as $\Delta\rho_n$ from thermal fluctuations.

The disagreement between the assumptions of these models can be resolved within a dynamical approach, where light nuclei are produced and destroyed continually as a result of reactions. Such an approach was recently suggested, but presently has been explored only for deuterons [18, 19]. It allows to determine, where and when deuterons are produced and resolve the tension between the extreme assumptions of the thermal and coalescence models—early production at hadronic chemical freeze-out versus late production at the stage, when nucleons received the full feed-down from resonances.

Of course, in addition to a realistic space-time picture any reasonable model of light nuclei production should properly take the known nuclear effects into account. In particular, recently it has been pointed out that the feed-down to tritons and deuterons from the numerous excited states of ^4He is important, especially at lower energies [20, 21]. Even if instead of the $\frac{N_t N_p}{N_d^2}$ ratio one considers a similar proton-free ratio

$$\frac{N_{^3\text{He}} N_t}{N_d N_\alpha}, \quad (48.8)$$

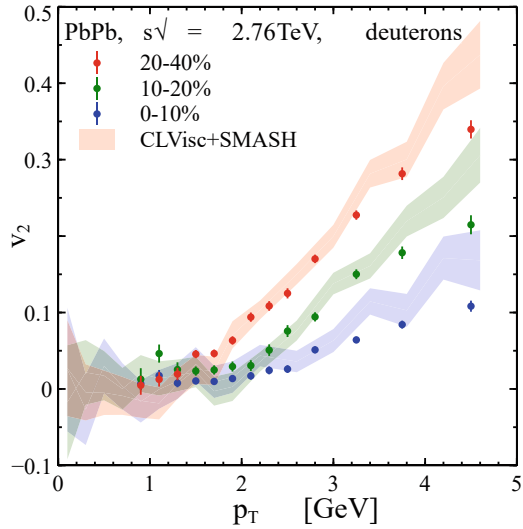
which is insensitive to resonances feed-down to protons (also insensitive to weak decays, for which the published STAR proton spectra are not corrected!), the decays of $^4\text{He}^*$ should still be taken into account.

48.2 Snowballs from Hell

The dynamical approach mentioned above suggests a solution to the following “snowballs in hell” puzzle [22]: midrapidity yields of light nuclei at LHC are described well by a thermal model with the temperature of hadronic chemical freeze-out $T_{chem} \approx 155$ MeV, while their spectra follow a blast-wave model with kinetic freeze-out temperature around $T_{kin} \approx 115$ MeV [16]. This poses the question, how light nuclei with binding energies of only few MeV (“the snowballs”) survive between chemical and kinetic freeze-outs (“the hell”). The puzzle is relevant for deuterons at a wide range of energies of $\sqrt{s_{NN}} = 5 - 5000$ GeV, and for other (anti-)nuclei (t , ^3He , $^3_\Lambda\text{H}$, ^4He , and their antiparticles) at 2.76 GeV. In contrast, as one can see in Fig. 48.1, tritons at lower energies are not described by the thermal model, therefore the puzzle is not persistent there. A possible solution of this puzzle was suggested for deuterons in a dynamical model [18, 19] and for other light nuclei in analytical models [23, 24]: the nuclei are destroyed and created, while their yield remains approximately constant over time.

The approach used in [18] is a hybrid approach combining relativistic hydrodynamics for the earlier stage of the reaction and hadronic transport for the later stage. The transformation between those, called particlization, is performed at $T = 155$ MeV, the temperature of the hadronic chemical freeze-out according to the thermal model. Thermal deuterons are sampled from hydrodynamics and allowed to rescatter in the hadronic afterburner, mainly via $\pi pn \leftrightarrow \pi d$ reactions. The amounts of these reactions in forward and reverse directions turns out to differ by less than 5% after $t > 15$ fm/c, and deuteron yield remains approximately unchanged. Nevertheless, the majority of the final deuterons are originating from the afterburner stage, not from hydrodynamics. Another option is tested in [18], where no deuterons are produced from the hydrodynamics at all, and therefore all deuterons originate from the afterburner. The resulting deuteron yield is then less by $\approx 20\%$, but is still consistent with experimental data.

Fig. 48.2 Elliptic flow of deuterons from the dynamical approach [18, 19] is compared to the data from ALICE [25]



As demonstrated in [18, 19], this approach is able to describe deuteron spectra in PbPb collisions at $\sqrt{s_{NN}} = 2.76\text{TeV}$ at different centralities. Here, in Fig. 48.2 we show that the deuteron elliptic flow $v_2(p_T)$ is also reproduced. This calculation was performed with deuterons being sampled at the particlization. It would be interesting to see, if these results change considerably in case of no deuterons sampled at particlization. An ongoing work is devoted to this question, as well as to testing the same mechanism at lower energies and for different nuclei.

48.3 Summary and Perspectives

In the last two years the interest to better understand light nuclei production in heavy ion collisions has increased considerably. There are at least two motivating challenges: precisely estimate the anti-nuclei flux in space from pp , pA , and AA collisions; and the search for the critical point of the strongly-interacting matter by measuring spatial density fluctuations using light nuclei production. The first challenge can in principle be resolved experimentally, but the second one needs precise models of nuclei production, where it would be possible to switch critical point effects on and off. No such model is currently available. Moreover, even models without critical point disagree on where and how the light nuclei are produced, see Fig. 48.1. This disagreement can be alleviated by dynamical simulations. The latter have already proven successful, resolving the “snowballs in hell” puzzle. To improve the dynamical models one needs more data on inclusive and exclusive inelastic cross sections of hadrons with light nuclei, such as $\pi + d$, $\pi + t$, $\pi + {}^3\text{He}$, $p + d$, $p + t$,

$p + {}^3\text{He}$, etc. The rates of reverse reactions that produce light nuclei can be computed from these cross sections using the detailed balance principle.

Simulations with some (but not all) critical point effects can be performed by supplying transport or hybrid simulation with an adjustable equation of state. In case of transport this can be a mean field potential tuned to provide an equation of state with a critical point. In hydrodynamics one can directly choose the equation of state with a phase transition, such as [26]. Certain care should be taken at the particlization to preserve the spatial fluctuations. A recently developed local microcanonical sampling approach [27] allows to address this difficulty. It is possible, that spatial fluctuations generated by the critical point and preserved by the proper particlization are still vanishing during the afterburner stage and are not influencing the light nuclei production. In this case the experimentally measured bumps in Fig. 48.1 may be related to the collision dynamics or to nuclear liquid-gas phase transition. These possibilities should not be dismissed and can be addressed with dynamical models in future.

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