The observation of light nuclei at ALICE and the $X(3872)$ conundrum

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The new data reported by ALICE on the production of light nuclei with $p_{\perp} \lesssim 10$ GeV in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV are used to compute an order-of-magnitude estimate of the expected production cross sections of light nuclei in proton-proton collisions at high transverse momenta. We compare the hypertriton, helium-3 and deuteron production cross sections to that of $X(3872)$, measured in prompt $pp$ collisions by CMS. The results we find suggest a different production mechanism for the $X(3872)$, making questionable any loosely bound molecule interpretation.

PACS numbers: 12.38.Mh, 14.40.Rt, 25.75.-q
Keywords: Hadron molecules, Nuclei production, Heavy ion collisions

As first discussed in [1], one expects a suppression of loosely bound hadron molecules in high energy $pp(\bar{p})$ collisions. Small relative momenta in the center of mass of such molecular hadrons, needed to preserve a state with few keV’s binding energies, are in fact hard to be obtained in hadron collisions at high energy and $p_{\perp}$.

Despite this, the $X(3872)$, one of the most studied loosely bound hadron molecule candidates [2], is strongly produced at the LHC – see e.g. [3]. This might simply be the indication that the $X$ hadron molecule interpretation is not correct (for the alternative tetraquark model, see [4–6]).

Assuming that final state interaction mechanisms are at work – whose description requires several model-dependent assumptions [7–8] – it has been proposed that the relative kinetic energy might be reduced in the center of mass of the hadron pair constituting the $X$, in such a way to match a shallow discrete level of some inter-hadron potential. A hadron molecule would then be formed, with a precise relation between binding energy and strong coupling to its constituent hadrons [9]. Since the mass and branching ratios of the $X$ have not been measured with the required precision yet, it is still unclear if this relation is fulfilled.

Final state interactions should also favor the prompt formation of $b$ona $f$ide light nuclei in high energy hadronic collisions. It would therefore be of great interest to measure the $pp$ (anti)deuteron production cross section in the same $p_{\perp}$ region where the $X$ has been observed [10].

Unfortunately, (anti)deuteron production in $pp$ collisions at $p_{\perp}$ values as high as $\approx 15$ GeV (where the $X$ is clearly seen at CMS [3]) has not been measured yet.

However, very recently the ALICE collaboration reported results on the production of deuteron, helium-3 ($^3$He) and hypertriton ($^3$H) light nuclei in relatively high $p_{\perp}$ bins in Pb-Pb collisions, at $\sqrt{s_{NN}} = 2.76$ TeV [11–12]. This is potentially a very exciting result for the reasons described above.

We would like to draw the attention on these data and propose a way to exploit them to provide an order-of-magnitude estimate of light nuclei production in $pp$ collisions, to compare with the $X$ data.

As a first approximation one can assume that there are no medium effects enhancing or suppressing the production of light nuclei in Pb-Pb collisions. This is equivalent to state that each nucleus-nucleus collision is just an independent product of $N_{\text{coll}}$ proton-proton collisions, with $N_{\text{coll}}$ computed in a Glauber Monte Carlo calculation as a function of the centrality class. We use the results from [13], which are compatible at 1σ level with the ALICE ones [14], and never more different than 3%. To compare with $\sqrt{s} = 7$ TeV data, we rescale our estimated cross sections by a factor $\sigma_{pp}^{\text{inel}}(7 \text{ TeV})/\sigma_{pp}^{\text{inel}}(2.76 \text{ TeV}) = 1.1$.

Consider for example the production of hypertriton observed by ALICE in Pb-Pb collisions. Neglecting medium effects, the $pp$ cross section can be estimated with

$$
\left( \frac{d\sigma \left( ^3\text{H} \right)}{dp_{\perp}} \right)_{pp} = \frac{\Delta y}{B( ^3\text{He }\pi )} \times \frac{1}{L_{pp}} \left( \frac{d^2N( ^3\text{He }\pi )}{dp_{\perp} dy} \right)_{pp} = \frac{\Delta y}{\sigma_{pp}^{\text{inel}}} \times \frac{\sigma_{pp}^{\text{inel}}}{N_{\text{evt}}} \left( \frac{1}{N_{\text{evt}}} \frac{d^2N( ^3\text{He }\pi )}{dp_{\perp} dy} \right)_{\text{Pb-Pb}}.
$$

ALICE analyzes $^3$He $\pi$ pairs, thus we need to divide by the branching ratio for the $^3$H $\rightarrow ^3$He $\pi$ decay – $B( ^3\text{He }\pi ) \approx 25\%$ [15] – in order to deduce the number

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1 In the following, the average of hypertriton and anti-hypertriton data is understood.
perform an exponential fit to the points in the region behavior, likely due to the expansion of the medium, we note that the selection of these events rejects any hypertriton decay products. Since the $^3$He data, which are produced in the primary vertex, are not corrected for the medium effects, nor the fact that the coalescence/recombination mechanism can be enhanced in Pb-Pb collisions [18]. In fact, such phenomena are known to favor the production of many-body hadrons with respect to the production of many-body hadrons.

Similarly, we can estimate the $^3$He distribution in $pp$ collisions from the ALICE Pb-Pb data in the 0-20% centrality class [12], using $N_{\text{coll}} = 1226$ [13]. We remark that the selection of these events rejects any $^3$He not produced in the primary vertex, i.e. the hypertriton decay products. Since the $^3$He data points with $p_{\perp} < 4.4$ GeV show a deviation from the exponential behavior, likely due to the expansion of the medium, we perform an exponential fit to the points in the region $p_{\perp} \in [4.45, 6.95]$ GeV only. Alternatively, we fit hypertriton and $^3$He data with the blast-wave model, which describes particle production properties by assuming thermal emission from an expanding source [17]. This model is expected to reproduce correctly the low and medium $p_{\perp}$ regions in Pb-Pb collisions. Since we are rescaling Pb-Pb data to $pp$ by a constant factor, the same shape holds in our estimated $pp$ data, and gives a guess on the asymptotic exponential behavior. The results are shown in Fig. 1.

Our rescaling to $pp$ collisions does not take into account neither medium effects, nor the fact that the coalescence/recombination mechanism can be enhanced in Pb-Pb collisions [18]. In fact, such phenomena are known to favor the production of many-body hadrons with respect to the production of many-body hadrons.

2 The blast-wave function is
\[
\frac{dN}{dp_{\perp}} \propto \int_0^R r dr m_{\perp} I_0 \left( \frac{p_{\perp} \sinh \rho}{T_{\text{kin}}} \right) K_1 \left( \frac{m_{\perp} \cosh \rho}{T_{\text{kin}}} \right),
\]
where $m_{\perp}$ is the transverse mass, $R$ is the radius of the fireball, $I_0$ and $K_1$ are the Bessel functions, $\rho = \tan^{-1} \left( \frac{(m_{\perp}^2 + 1/4)(r/R)}{2} \right)$, and $\langle \beta \rangle$ the averaged speed of the particles in the medium.
well known that the interaction of elementary partons, constituents close enough in phase space. However, it is difficult to produce the con-

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pp deuteron cross section, which is directly measured in respect to the X would fall short by about 2\(\div\)3 orders of magnitude with respect to the zero temperature case due to the well-known jet quenching effect [26, 27]. This would favor their coalescence into the final bound state by reducing their relative momenta directly at parton level.

The coalescence model is based on the sudden approximation 3 and is implemented by calculating the overlap of the density matrix of the constituents with the Wigner function of the final composite particle. In particular, it has the important property of taking into account the inner structure of the considered hadron. If one only requires vicinity in momentum space, the \(p_\perp\) distribution of a composite state with \(N\) constituents coming out of a hot QCD medium is roughly given by

\[
\frac{dN_b}{dp_\perp(p_\perp)}(p_\perp) \sim \prod_{i=1}^{N} \frac{dN_i}{dp_\perp(p_\perp/N)},
\]

where \(N_b\) is the number of final bound states and \(N_i\) is the number of produced constituents. This would also explain why in Fig. 1 the cross section for the \(^3\)He and hypertriton are several orders of magnitude smaller than the deuteron one: one additional \(p\) or \(\Lambda\), close enough in phase space, must be produced.

It has already been shown that coalescence effects in Pb-Pb collisions can have relevant consequences on the production of multi-quark states. In particular, molecular states with small binding energy are expected to be enhanced, i.e., \(R_{AA} \gtrsim 1\) [25].

Unfortunately there is no measurement of \(R_{AA}\) for the deuteron as a function of \(p_\perp\). However, there is another nuclear modification factor which is often used,

\[
R_{CP} = \frac{\left(\frac{1}{N_{\text{evt}} d^2N}{dp_\perp dy}\right)_{\text{Pb-Pb}}}{\left(\frac{1}{N_{\text{coll}} d^2N}{dp_\perp dy}\right)_{\text{pp}}^{0.1-10\%}},
\]

\[
R_{CP} = \frac{\left(\frac{1}{N_{\text{evt}} d^2N}{dp_\perp dy}\right)_{\text{Pb-Pb}}^{60-80\%}}{\left(\frac{1}{N_{\text{coll}} d^2N}{dp_\perp dy}\right)_{\text{Pb-Pb}}^{60-80\%}},
\]

which compares the particle yield in Pb-Pb collisions with that in pp. It then follows that the method used to obtain Eq. (1) corresponds to assume \(R_{AA} = 1\).

While for ordinary hadrons medium effects generally lead to a suppression of the particle yield – i.e., \(R_{AA} < 1\) – conversely they can favor the production of hadronic molecules. The role of the medium would be, in fact, that of decreasing the relative momenta of the components with respect to the zero temperature case due to the well-known jet quenching effect [26, 27]. This would favor their coalescence into the final bound state by reducing their relative momenta directly at parton level.

For the deuteron we use ALICE pp data [12] to estimate

\[
\left(\frac{d\sigma}{dp_\perp}\right)_{pp} = \frac{1}{N_{\text{pp}}^{\text{inel}}} \int d^2N(d)_{pp} dp_\perp dy_{pp} \equiv \Delta y \times \sigma_{pp}^{\text{inel}} \left(1 + \frac{1}{N_{\text{pp}}^{\text{inel}}} \int d^2N(d)_{pp} dp_\perp dy_{pp}\right)
\]

(2)

\(N_{\text{pp}}^{\text{inel}}\) being the number of pp inelastic collisions collected. We perform the fit to the points in the region \(p_\perp \in [1.7, 3.0]\) GeV, which shows a good exponential behaviour.

The CMS analysis of \(X\) production provides the differential cross section times the branching fraction \(B(X(3872) \rightarrow J/\psi \pi^+ \pi^-)\). The latter has not been measured yet, and the lower limit reported in the PDG is \(B > 2.6\%\) [19]. An estimate for the upper limit has been reported, \(B < 6.6\%\) at 90\% C.L. [20]; we use instead the more conservative value \(B = 8.1^{\pm 3.1}_{\pm 0.7}\%\) [6]. The comparison in Fig. 1 shows that, according to the most conservative exponential fit in the left panel, the extrapolated hypertriton production cross section in pp collisions would fall short by about 2\(\div\)3 orders of magnitude with respect to the \(X\) production, and much more according to the blast-wave fit in the right panel. The drop of the deuteron cross section, which is directly measured in pp collisions, appears definitely faster.

As we mentioned already, the main problem for the production of loosely bound molecular states in proton-proton collisions is the difficulty in producing the constituents close enough in phase space. However, it is well known that the interaction of elementary partons with the collective hot dense medium causes relevant energy loss of the partons themselves. This effect is usually quantified by the nuclear modification factor [21, 25]
This quantity is a comparison between the most central and the most peripheral Pb-Pb collisions and therefore provides another valid indicator of the strength of medium effects (which should be absent in the less dense, most peripheral events). The fact that \( R_{AA} \) and \( R_{CP} \) measurements for hadron species are strongly correlated to each other is shown experimentally by a thorough data analysis reported by ATLAS [23], up to very high \( p_\perp \sim 100 \text{ GeV} \).

Using the ALICE data presented in [11] we can compute \( R_{CP} \) for deuteron as a function of \( p_\perp \) and compare it with that for generic charged tracks, as reported in [23] – see Fig. 2. We use \( N_{\text{coll}}^{60\%-80\%} = 27.5 \) [13]. As one immediately notices, the difference from ordinary hadrons is

\[ \text{N} \rightarrow \text{He and} \]

\[ \text{see Fig. 2. We use it with that for generic charged tracks, as reported in [23].} \]

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The presence of the QCD medium is extremely effective at enhancing the production of deuteron for the reasons explained before. In fact, \( R_{CP} \) for this hadronic molecule becomes larger than unity for \( p_\perp \gtrsim 2.5 \text{ GeV} \), in particular we have \( R_{CP} = 1.7 \) at the last point with \( p_\perp = 3.1 \text{ GeV} \). Using the blast-wave fitting function for the peripheral data taken from [11], we also extrapolate up to the end point of the central data, confirming the growth of \( R_{CP} \) with \( p_\perp \).

We expect a similar behavior in \( R_{AA} \), in particular a value larger than 1 for \( p_\perp \) large enough.

To get an independent rough estimate for \( R_{AA} \), we assume the deuteron production cross section in \( pp \) collisions to scale with \( \sqrt{s} \) like the inelastic cross section, and compare the ALICE data in central Pb-Pb collisions at \( \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \), with the ones in \( pp \) collisions at \( \sqrt{s} = 7 \text{ TeV} \) [12]. Indeed, we find that \( R_{AA} \) exceeds 1 at \( p_\perp = 2.1 \text{ GeV} \), and reaches 5 at \( p_\perp = 4.3 \text{ GeV} \). This gives strength to our expectation for \( R_{AA} > 1 \). To display the size of this effect, we plot also the hypertriton curves for \( R_{AA} = 5 \) in Fig. 1.

One naturally expects for a similar enhancement to be even more relevant for 3-body nuclei like \(^3\text{He} \) and hypertriton. Its role would be to further decrease the extrapolated cross section in prompt \( pp \) collisions. As we already said, indeed, a value of \( R_{AA} > 1 \) applied to Pb-Pb data implies a \( pp \) cross section even smaller than predicted by the Glauber model. Even though qualitative conclusions can already be drawn, a quantitative analysis substantiated by data at higher \( p_\perp \) is necessary for a definitive comparison with the X case.

Even assuming that only a hot pion gas is excited in Pb-Pb collisions, there would likely be a large number of final state interactions with pions catalizing the formation of a loosely bound hypertriton along the lines discussed in [6] [10] [29]. In any case, such an environment is present in the Hadron Resonance Gas corona formed when the outer shell of the QCD medium cools down [30].

In summary, the extrapolation of deuteron and \(^3\text{He} \) data in \( pp \) collisions shown in Fig. 1 suggests that loosely bound molecules are hardly produced at high \( p_\perp \). The extrapolated curve of hypertriton data from Pb-Pb collisions might lead to milder conclusions although we expect it should be significantly suppressed when medium effects are properly subtracted. Such effects are indeed already sizeable for the deuteron as shown in Fig. 2, and probably even more relevant for 3-body nuclei.

We are aware that for an unbiased and definitive comparison with X production at \( p_\perp \) as high as 15 GeV, deuteron (or hypertriton) should be searched in \( pp \) rather than in Pb-Pb to avoid the complications of subtracting medium effects. These analyses can be performed by ALICE and LHCb during Run II. One of the purposes of this letter is to further motivate the required experimental work.

Acknowledgments: We wish to thank M. Gyulassy for valuable discussions on medium effects and C. Hanhart for pointing the ALICE results to us. We also thank M.A. Mazzoni for interesting comments and suggestions, and S. Bufalino, A. Caliva, G. Cavoto, B. Domenigus, A.P. Kalweit, R. Lea for clarifications on data published by the ALICE collaboration.

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