

The behavior of the deuteron in a hadronic environment

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²PHYSICAL REVIEW D **113**, 014003 (2026)

- Study of the interactions of hadron states during the hadron gas phase produced in heavy ion collisions (HICs)
- Estimation of their final yield
- Example: the deuteron



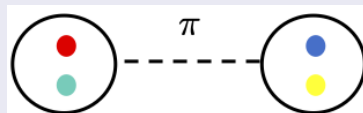
Motivation

Exotic hadron states

- Production, composition and binding mechanisms → debate

Hadron molecule

- Large $\sim 5 - 10$ fm
- Interactions: meson exchange
- Weakly bound



Compact tetraquark

- Compact structure $\sim 0.5 - 1$ fm
- Fundamental strong interactions
- Strongly bound



Challenge: Hadron production in HICs

Early stages of HIC's

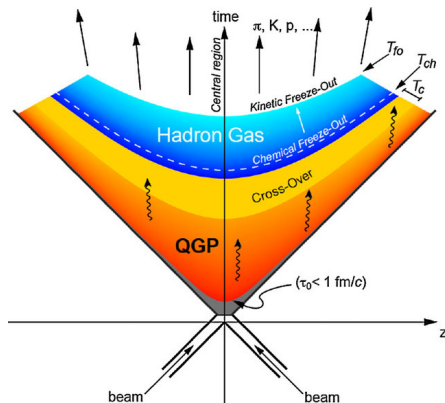
- Q 's coalesce $\rightarrow$ multiquarks
- Absorption/regeneration

Hadron gas phase (HGP)

- Multiquarks: interact
- Multiquark interpretation $\rightarrow$ influence on the observables

Naive expectation

- Molecules $\rightarrow$ destroyed
- Compact $4q$'s $\rightarrow$ undisturbed
- HGP $\rightarrow$ filter



[Braun-Munzinger and Donigus, Nucl. Phys. A 987 (2019)

144]



CERN COURIER | Reporting on international high-energy physics

Physics ▾

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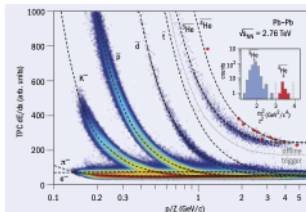
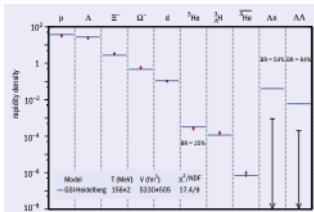
Magazine

STRONG INTERACTIONS | FEATURE

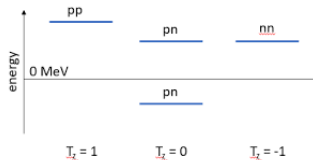
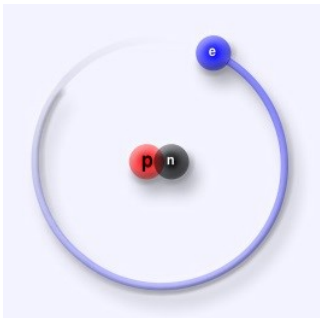
ALICE investigates 'snowballs in hell'

26 August 2015

How is it that loosely bound objects are observed in high-energy nuclear collisions?



The deuteron



Source: Energy Education, "Deuterium".

- The only stable state for 2 N 's
- A valuable tool observed in HICs
- The prototypical shallow hadronic molecule:

$$E_b = 2.2\text{MeV}$$

$$I(J^P) = 0(1^+)$$

$$\begin{aligned} |d\rangle &\equiv |I = 0, I_3 = 0\rangle \\ &\equiv \frac{1}{\sqrt{2}}(|pn\rangle - |np\rangle) \end{aligned}$$

- Weinberg's compositeness: pn bound state



The Deuteron (d)

- d : a crucial benchmark for understanding more complex molecular candidates such as the $X(3872)$
- ALICE (2023): N_d compatible with both the thermal model (SHM) and the UrQMD (hybrid-) model
- Thermal model [Andronic *et al.* (2017)]: N_d from fitting (T_H, μ, V_H)
- UrQMD [Reichert *et al.* (2023)]:
Ultra-relativistic-Quantum-Molecular-Dynamics approach
- Coalescence model (COM) [EXHIC (2017)]: information about the intrinsic structure
- Both SHM, COM do not include the dynamics of how the deuteron and their constituents interact with the hadron gas

Natural questions

- Influence of the medium during the HGP on final yield N_d ?
- Does N_d retain memory of its initial production mechanism?

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Our contribution $\Rightarrow$ interactions of the d with the medium

Hadronic Interactions $\Rightarrow$ Effective approach



Amplitudes $\Rightarrow$ Cross Sections $\Rightarrow$ Therm. Av. Cross Sections



Initial Conditions (SHM, COM) + Bjorken picture $\Rightarrow$ Kinetic (rate) equation

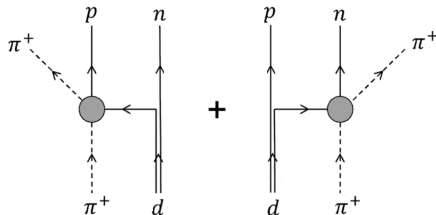


Time Evolution of N_d



Reaction $d\pi \rightarrow NN'\pi$

Quasi-free approximation



$\lambda_\pi \approx 0.5 \text{ fm} \ll d_d \approx 4 \text{ fm}$
 π interacts with each nucleon

$d\pi$ system

$$|d\pi\rangle = \frac{1}{\sqrt{2}} [|p\pi\rangle |n'\rangle - |n\pi\rangle |p'\rangle].$$

Scattering

$$\langle d\pi^+ | \hat{T} | pn\pi^+ \rangle = T^+ + \sum_a T_{\text{BW}}^{(a)}$$

T^+ : average over the $l = 3/2$ and $l = 1/2$ channels;

$T_{\text{BW}}^{(a)}$: Breit-Wigner amplitude

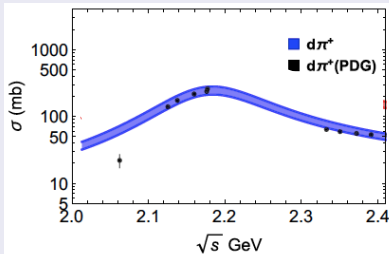
Lowest-energy peak: $\mathcal{D}(2180)$

TABLE I. Parameters for the Breit-Wigner amplitudes obtained from the fit to the PDG cross-section data [41].

Parameter	$\mathcal{D}(2180)$
M_{BW} (GeV)	2.180
$\Gamma(M_{\text{BW}})$ (GeV)	0.070
q_0 (GeV)	0.9
$g_a = g_b$	6.5
l	1
α	7.0 ± 0.5

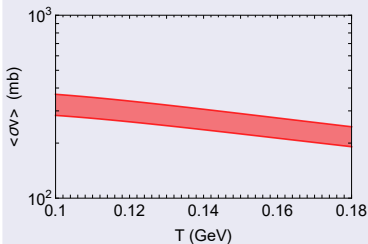


Vacuum Cross Section



- Reasonable description of the data in the low-energy region
- Hadron gas: $T \leq 160$ MeV
- higher-energy deviations: small impact on $\langle \sigma_{ab \rightarrow cd} v_{ab} \rangle$

Thermally-Averaged Cross Section



$$\langle \sigma_{ab \rightarrow cd} v_{ab} \rangle = \frac{\int d^3 \mathbf{p}_a d^3 \mathbf{p}_b f_a(\mathbf{p}_a) f_b(\mathbf{p}_b) \sigma_{ab \rightarrow cd} v_{ab}}{\int d^3 \mathbf{p}_a d^3 \mathbf{p}_b f_a(\mathbf{p}_a) f_b(\mathbf{p}_b)}$$

- Non-negligible magnitude
- mild decreasing trend across the temperature range
- Smooth energy variation over the energy range of the cross section where the thermal distribution is significant

The momentum-integrated evolution equation of the d multiplicity

$$\frac{dN_d(\tau)}{d\tau} = \langle \sigma_{NN' \rightarrow d\pi} v_{NN'} \rangle n_{NN'}(\tau) n_\pi(\tau) V(\tau) - \langle \sigma_{d\pi \rightarrow NN' \pi} v_{d\pi} \rangle N_d(\tau) n_\pi(\tau)$$

$n_i(\tau)$: thermal-equilibrium densities of π, N, N' at proper time τ

Boost invariant Bjorken picture with accelerated transverse expansion:

$$T(\tau) = T_C - (T_H - T_F) \left(\frac{\tau - \tau_H}{\tau_F - \tau_H} \right)^{\frac{4}{5}},$$

$$V(\tau) = \pi \left[R_C + v_C (\tau - \tau_C) + \frac{a_C}{2} (\tau - \tau_C)^2 \right]^2 \tau_C.$$

ExHIC Collab. Prog. Part.
Nucl. Phys. 95, 279 (2017)
(PbPb at $\sqrt{s_{NN}} = 5.02$ TeV)

v_C (c)	a_C (c ² /fm)	R_C (fm)
0.5	0.09	11
τ_C (fm/c)	τ_H (fm/c)	τ_F (fm/c)
7.1	10.2	21.5
T_C (MeV)	T_H (MeV)	T_F (MeV)
156	156	115
N_π	ω_d [MeV]	$N_p = N_n$
713	13.2	32

Initial Conditions

Statistical Hadronization Model (SHM) [T_H, μ, V_H]

$$N_h^{(SHM)}(\tau_H) \approx \frac{1}{2\pi^2} \gamma_i g_h m_h^2 T(\tau_H) K_2 \left(\frac{m_h}{T(\tau_H)} \right)$$

Coalescence Model (COM)

$$\begin{aligned} N_h^{(Coal)}(\tau_C) &\equiv g_h \prod_{i=1}^n \frac{1}{g_i} \int \frac{p_i \cdot d\sigma_i}{(2\pi)^3} \frac{d^3 p_i}{E_i} f(x_i, p_i) \times f_W(x_1, \dots, x_n; p_1, \dots, p_n) \\ &\approx g_h \prod_{j=1}^n \frac{N_j}{g_j} \prod_{k=1}^{n-1} \frac{(4\pi\sigma_k^2)^{\frac{3}{2}}}{V(\tau_C)(1 + 2\mu_k T(\tau_C) \sigma_k^2)} \left[\frac{4\mu_k T(\tau_C) \sigma_k^2}{3(1 + 2\mu_k T(\tau_C) \sigma_k^2)} \right]^{l_i} \end{aligned}$$

$f(x_i, p_i)$: phase-space distribution function of the constituents in the emission source;
 $f_W(x_1, \dots, x_n; p_1, \dots, p_n)$: Wigner function of the produced hadron; l_i : angular mom.

$\sigma_i = (\mu_i \omega)^{-1/2}$; ω : oscillator frequency; $\omega = 6E_b$

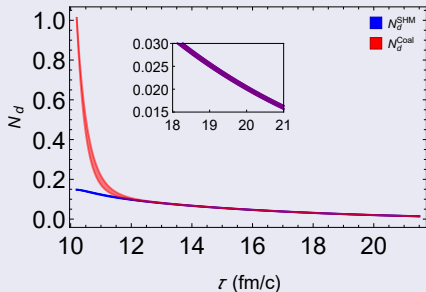
Statistical Model

$$N_d^{(SHM)}(\tau_H) \approx 0.15$$

Coalescence Model

$$N_d^{(Coal)}(\tau_H) \approx 1.01$$





Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV

Statistical Hadronization Model

$N_d^{(SHM)}$: decrease, retaining a small fraction of its initial yield

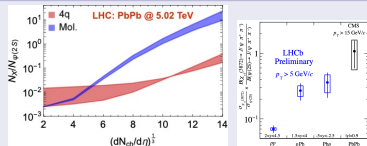
Coalescence Model

$N_d^{(Coal)}$: rapid depletion, with a stabilization at $\tau \gtrsim 14$ fm/c; suffers even more severe attenuation of its large initial N_d

- Fast convergence $\rightarrow$ chemical equilibrium
- $N_d(\tau_F)$: governed by the scattering processes in the hadronic medium
- Insensitive to the production mechanism $\rightarrow$ SHM and COM agree!
- The medium: *erases* the memory of the initial stages
- It aligns with previous analysis [SMASH, PRC **104**, 034908 (2021)]
- Interactions of d with the medium: microscopic basis for the SHM

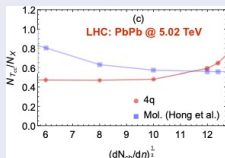
Other analyses

$X(3872) [(cq\bar{c}\bar{q}); 0(1^{++})]$



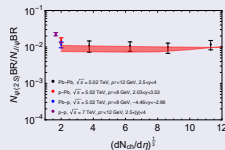
[PRD **90**, 114023 (2014); **105**, 116029 (2022); **110**, 014011 (2024); PTEP **2016**, 103B01 (2016), PLB **761**, 303 (2016); EPJC (2022); ...] $N(4q) < N(Mol.)$; $R \sim Data$

$T_{cc}^+(3875) [(cc\bar{q}\bar{q}); 0(1^+)]$



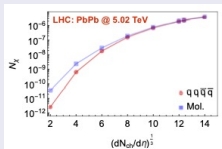
[EPJC **82**, 296 (2022); PRD **105**, 116029 (2022); NPB **985**, 115994 (2022)]

$\Psi(2S) [(c\bar{c}); 0(1^{--})]$



PRC **97**, 044902 (2018); PLB **864**, 139407 (2025)]

$\chi_{c1}(4274) [(cs\bar{c}\bar{s}); 0^+(1^{++})]$



[PRD **108**, 096028 (2023); PRD **109**, 014041 (2024)]

[Collaboration USP-UNIFESP-UFBA: Navarra, Nielsen, Torres, Kamchandani, LMA, Bertunlani (Texas) ...]

Summary

- Naive expectation: shallow bound states do not survive to the HGP, differently of the tetraquarks
 - Deuterons (molecules): observed! How are they produced?
 - Influence of the medium on final yield ?
-
- Final yield: governed by the scattering reaction within the medium
 - SHM and COM predictions agree!
 - The medium: *erases* the memory of the initial stages
 - Microscopic justification of the SHM

Thank You!!!

Financial support:



Thermally averaged cross sections

$$\begin{aligned}\langle \sigma_{ab \rightarrow cd} v_{ab} \rangle &= \frac{\int d^3 \mathbf{p}_a d^3 \mathbf{p}_b f_a(\mathbf{p}_a) f_b(\mathbf{p}_b) \sigma_{ab \rightarrow cd} v_{ab}}{\int d^3 \mathbf{p}_a d^3 \mathbf{p}_b f_a(\mathbf{p}_a) f_b(\mathbf{p}_b)} \\ &= \frac{1}{4\alpha_a^2 K_2(\alpha_a) \alpha_b^2 K_2(\alpha_b)} \\ &\quad \times \int_{z_0}^{\infty} dz K_1(z) \sigma(s = z^2 T^2) \\ &\quad \times \left[z^2 - (\alpha_a + \alpha_b)^2 \right] \left[z^2 - (\alpha_a - \alpha_b)^2 \right],\end{aligned}$$

v_{ab} : relative velocity of initial two interacting particles a and b ;

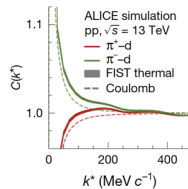
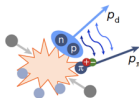
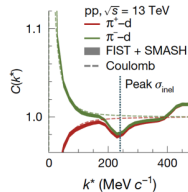
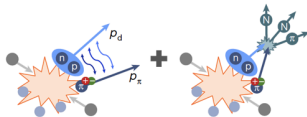
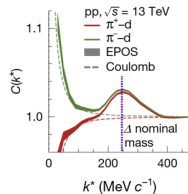
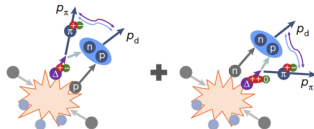
$f_i(\mathbf{p}_i)$: Bose-Einstein distribution (of particles of species i);

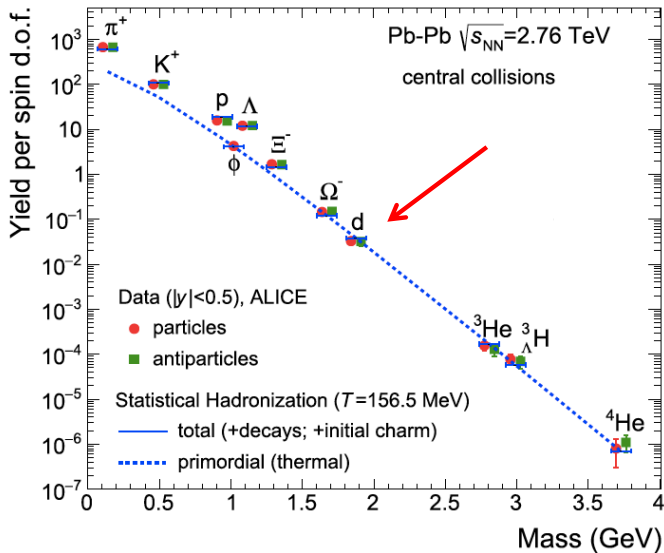
$\alpha_i = m_i / T$;

$z_0 = \max(\alpha_a + \alpha_b, \alpha_c + \alpha_d)$;

K_1 and K_2 the modified Bessel functions of second kind.

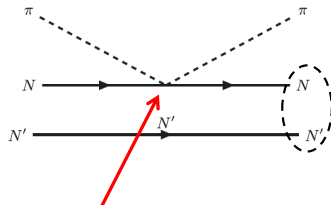
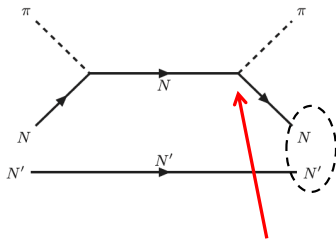


a**b****c**



Physics Letters B 797 (2019) 134836





$$\mathcal{L}_{\text{int}} = -\frac{1}{2} \frac{g_A}{F_\pi} \bar{N} \gamma^\mu \gamma_5 \partial_\mu \vec{\pi} \cdot \vec{\tau} N - \frac{1}{4F^2} \bar{N} \gamma^\mu \vec{\pi} \times \partial_\mu \vec{\pi} \cdot \vec{\tau} N,$$



$$\mathcal{M}_s = i \frac{g_A^2}{4F_\pi^2} \bar{u}(p') \left[2m_N + \frac{1}{2}(\not{q} + \not{q}') \left(-1 - \frac{2m_N}{v - v_B} \right) \right] \tau_b \tau_a u(p),$$

$$\mathcal{M}_u = i \frac{g_A^2}{4F_\pi^2} \bar{u}(p') \left[2m_N + \frac{1}{2}(\not{q} + \not{q}') \left(1 - \frac{2m_N}{v + v_B} \right) \right] \tau_b \tau_a u(p)$$

$$\mathcal{M}_{cont} = i \frac{1}{2F_\pi^2} \bar{u}(p') \frac{1}{2}(\not{q} + \not{q}') \frac{1}{2} [\tau_b, \tau_a] u(p)$$

$$v = \frac{s - u}{4m_N}$$

$$v_B = \frac{t - 2m_\pi^2}{4m_N}$$



$$T_{ab}(p, q; p', q') = \delta_{ab} T^+(p, q; p', q') - i \epsilon_{abc} \tau_c T^-(p, q; p', q')$$

$$T^+ = \frac{g_A^2}{4F_\pi^2} \bar{u}(p') \left[2m_N + \frac{1}{2} (\not{q} + \not{q}') \left(-1 - \frac{2m_N}{v - v_B} \right) \right] u(p) \\ + \frac{g_A^2}{4F_\pi^2} \bar{u}(p') \left[2m_N + \frac{1}{2} (\not{q} + \not{q}') \left(1 - \frac{2m_N}{v + v_B} \right) \right] u(p).$$

$$T^- = \frac{g_A^2}{4F_\pi^2} \bar{u}(p') \left[2m_N + \frac{1}{2} (\not{q} + \not{q}') \left(-1 - \frac{2m_N}{v - v_B} \right) \right] u(p) \\ - \frac{g_A^2}{4F_\pi^2} \bar{u}(p') \left[2m_N + \frac{1}{2} (\not{q} + \not{q}') \left(1 - \frac{2m_N}{v + v_B} \right) \right] u(p) \\ + \bar{u}(p') \frac{(\not{q} + \not{q}')}{4F_\pi^2} u(p).$$



$$\pi_a(q) + N(p) \rightarrow \pi_b(q') + N(p')$$

$$T_{\text{BW}}^{(a)} = \bar{u}(p')(\not{q} + \not{q}')\mathcal{A}_a(s)u(p).$$

$$\mathcal{A}_a(s) = \frac{\mathcal{N}_a(s)}{M_{\text{BW}}^2 - s - iM_{\text{BW}}\Gamma(s)},$$

