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Hypernuclei at relativistic energies

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Abstract. This article summarizes some of the current theoretical developments and the experimental status of hypernuclei in relativistic heavy-ion collisions and elementary collisions. In particular, the most recent results of hyperhydrogen of mass $A = 3$ and 4 are discussed. The highlight at SQM2022 in this perspective was the discovery of the anti-hyperhydrogen-4 by the STAR Collaboration, in a large data set consisting of different collision systems. Furthermore, the production yields of hyperhydrogen-4 and hyperhelium-4 from the STAR Collaboration can be described nicely by the thermal model when the excited states of these hypernuclei are taken into account. In contrast, the production measurements in small systems (pp and p–Pb) from the ALICE Collaboration tends to favour the coalescence model over the thermal description. New measurements from STAR, ALICE and HADES Collaborations of the properties, e.g. lifetime, of $A = 3$ and 4 hypernuclei give similar results of these properties. Also the anti-hyperhydrogen-4 lifetime is in rather good agreement with previous measurements. Interestingly, the new STAR measurement on the R_3 value, that is connected to the branching ratio, points to a Λ separation energy that is below 100 keV but definitely consistent with the value of 130 keV assumed since the 70s.

1 Introduction

Hypernuclei are composite objects, consisting of nucleons (protons and neutrons) and at least one hyperon. So the theoretical description of these systems needs to take into account the hyperon-nucleon interaction and in cases where there are more than one hyperon also the hyperon-hyperon interaction. The fact that scattering data on their interactions was scarce yet, led basically to the tenor that the main source of information are hypernuclei. Only recently new experiments started (see for instance [1, 2]) that will help to constrain the existing models better, e.g. [3–6]. In addition, the hyperon-nucleon and hyperon-hyperon interaction can also be studied through intensity correlations of the Hanburry Brown and Twiss type [7–9] (nowadays often called femtoscopy, since the experimental technique was used to measure sizes of the emitting source in high-energy collisions leading to values of few femtometer). Examples and more details of how the technique is applied, in particular how that can be used to extract interaction parameters, can be found in [10].

The hyperon-hyperon and hyperon-nucleon interactions might also become important in case higher (energy) densities are reached in neutron stars. The study of the appearance of hyperons in neutron stars led to the so called "hyperon puzzle" [11]. This is connected to

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a weakening of the equation-of-state and thus the often discussed impossibilty to describe the observed neutron star masses of above two solar masses when hyperons are involved. Recently, the solution was seen in the necessity of three-body forces that have been neglected before [12–14]. This could be avoided if the used interactions are modified according to the results from femtoscopy [10].

Of particular interest is the lightest hypernucleus, the hypertriton ${}^{3}_{\Lambda}$H. It consists of a proton,

Symbol	Name	Decay Modes	Mass (GeV/c^2)	B_Λ (MeV)	$\sqrt{\langle r^2 \rangle}$ (fm)
${}^{3}_{\Lambda}$H	hypertriton	^{3}He + π^- d + p + π^-	2.9911	0.162	4.9
${}^{4}_{\Lambda}$H	hyperhydrogen-4	^{4}He + π^- ^{3}H + p + π^-	3.9224	2.169	2.0
${}^{4}_{\Lambda}$He	hyperhelium-4	^{3}He + p + π^-	3.9217	2.347	2.0

Table 1. Compilation of properties of A = 2 and 3 hypernuclei discussed in this article. Decay modes listed are the mesonic decays not containing neutral particles. The mass and binding energies are from [15]. The size in the last column is the rms radius ($\sqrt{\langle r^2 \rangle}$) calculated in Ref. [16].

a neutron and a Λ hyperon. Since the Λ separation energy ($B_\Lambda = 0.162 \pm 0.044$ MeV [15] is so small it is often imagined as a deuteron core with a Λ with a distance of about $\sqrt{\langle r^2_{\mathrm{d}\Lambda} \rangle} \approx 10.6$ fm [17, 18]. If one does a more sophisticated calculation [16, 18, 19] one can also determine the rms radius ($\sqrt{\langle r^2 \rangle}$) of the whole object. Table 1 gives some infromation on the hypernuclei that are discussed here. One clearly sees that the A = 4 hypernuclei are more bound and therefore also slightly more compact than the hypertriton.

1.1 Thermal model

The thermal model description of production yields dN/dy of hadrons works well also for light nuclei (as can be seen from Fig, 1, where the yield dN/dy is shown as function of the collision energy $\sqrt{s_{\mathrm{NN}}}$ from thermal model prediction [25], together with (anti-)deuteron measurements from the STAR BES [23] and ALICE results for different nuclei [20–22]). The measured yields in heavy-ion collisions are rather well described by using a grand-canonical ensemble, leading to three free parameters, i.e. chemical freeze-out temperature T_{ch}, volume V and baryo-chemical potential μ_{B}. In case of small multiplicities per event one needs to

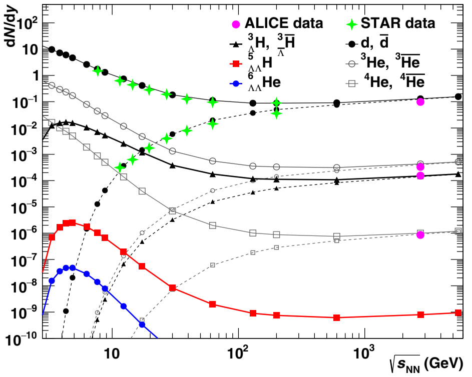

Figure 1. Themal model predictions for the production of several nuclei and hypernuclei, together with experimental results of the ALICE Collaboration [20–22] and the STAR Collaboration [23]. Figure from [24].

use instead a canonical ensemble. There a correlation volume V_c (or correlation radius R_c) is needed in addition, in which the corresponding quantum numbers (typically charge Q, baryon number B and/or strangeness S) are conserved expicitly [26, 27].

At the LHC $\mu_B \approx 0$, therefore often a value of zero is assumed in fits and that works well. Recent studies of yield ratios, also involving the hypertriton measurements, lead to a very precise determination of μ_B, for more details see [28]. The volume V is mainly determined by the pion yields so T_{ch} is the main parameter, which allows to describe the yields of many (anti-)hadrons over ten orders of magnitude [29].

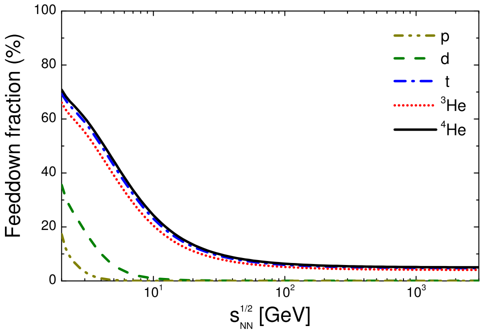

Figure 2. Fractions of final yields of p, d, t, ^{3}He, and ^{4}He coming from decays of the excited nuclei estimated in the thermal model, from [30]

The experimental (final) yields of hadrons suffer typically from large feeddown from higher mass states (resonances, that decay strongly or electromagnetically, since week decays are experimentally separable), that increase the yield from the (primordial) expectation based only on the quantum numbers and mass of the particular state. For the thermal model description of the yields of light nuclei it seems from a first side that there is no feeddown to be taken into account [31, 32]. That is at least for collision energies above $\sqrt{s_{NN}} > 20$ GeV the case, since feed down fractions from excited nuclei into stable ones are below 10% [30]. This can be seen from Fig. 2. At the LHC the feeddown is negligible for deuterons and only about 5% for ^{3}H, ^{3}He and ^{4}He, which is currently covered by the experimental uncertainties.

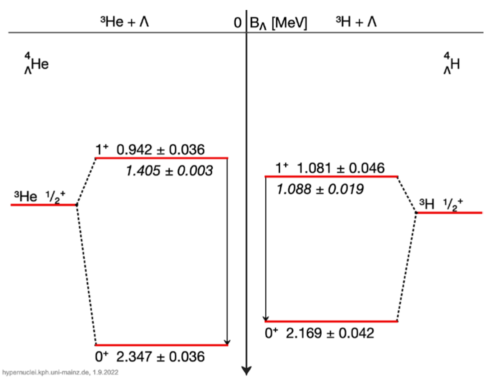

Figure 3. Binding energy level scheme of $A = 4$ hypernuclei. Directly taken from [15]

For the hypertriton there are no excited states known. This is different for $A = 4$ hypernuclei, where both states ($^4_\Lambda$H and $^4_\Lambda$He) have an excited state that is decaying into the ground state by emission of a photon of about one MeV as visible from Fig. 3. That means that the yield of the ground state is significantly higher than expected, without taking the excited state into account. A rough estimate can be given already from the degeneracy (as visible from Fig. 3): with $g = 2J + 1$ one gets $g(^4_\Lambda\mathrm{H}) = 1$ and $g(^4_\Lambda\mathrm{H}^*) = 3$, so the expected yield is four times as high, whereas a factor one comes from the ground state and a factor three from the excited state (the same holds for the $^4_\Lambda$He).

2 Hypernuclei

2.1 Production

New and important results have been shown and discussed in the context of the production of (anti-)hypernuclei. The highlight at SQM2022 was definitely the observation of the anti-hyperhydrogen-4 $^4_{\overline{\Lambda}}\overline{\mathrm{H}}$ by the STAR Collaboration [33] in a huge data set of different collision systems (Au–Au, U–U, Zr–Zr and Ru–Ru) and data taking campaigns. This also showed a nice agreement with the above mentioned factor four enhancement, compared for the case when only the ground is taken into account. That is also in agreement with the results for the production of $^4_\Lambda$H and $^4_\Lambda$He in the high statistics data at $\sqrt{s_{\mathrm{NN}}}$ = 3 GeV [34].

The biggest tension for the thermal model at the moment comes from the measurements in small systems (pp and p–Pb) by the ALICE Collaboration [35, 36]. These results give a significant tension for the canonical thermal model expectation [27] and seem to favour the coalescence model [37, 38].

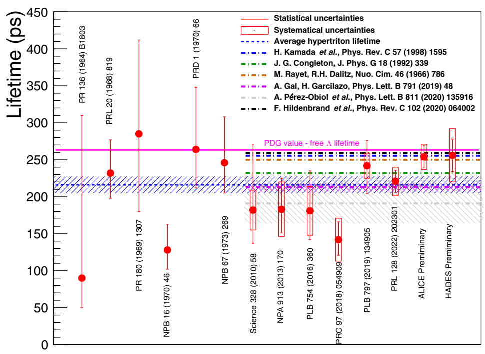

Figure 4. Hypertriton lifetime measured by the ALICE, HADES, HypHI and the STAR Collaborations in heavy-ion collisions, compared with previously published results. The blue dashed line with the shaded band represents the world average of the shown hypertriton lifetime measurements. The magenta full horizontal line indicates the lifetime of the free Λ hyperon as reported by the Particle Data Group [39]. The dashed-dotted lines of different colours are theoretical model expectations of the hypertriton lifetime. Figure updated from [24]

2.2 Lifetime, Branching Ratio and Binding Energy

A very active field from our community is also connected to measure properties of hypernuclei in high precision (in particular since the large data sets contain large numbers of hypernuclei). The first results about ten years ago were on the lifetime of the hypertriton and then several measurements followed becoming more and more precise (as shown in Fig. 4). The first four measurements from heavy-ion collisions (STAR, HypHI, ALICE) aligned well at a central value significantly below the free Λ lifetime. From the aforementioned low Λ separation energy and the corresponding halo-like structure ($\sqrt{\langle r^2_{\mathrm{d}\Lambda}\rangle} \approx 10.6$ fm) the lifetime of the hypertriton is expected to be very close to the free Λ lifetime. One might say that from the current most situation is cleared up, but taking all measurements (also the new preliminary result from HADES [40]) into account and building an average (visible from the blue dashed line in Fig. 4 and the resulting uncertainty in the blue shaded band) one gets a 4.2σ distance even taking the uncertainty of the PDG value of the Λ [39] into account. So from that perspective the "hypertriton puzzle" [17] is not solved yet.

HADES and STAR Collaborations [33, 34, 40] also have shown results on the lifetime of the hyperhydrogen-4 and STAR also on the hyperhelium-4. There is no puzzle for these hypernuclei since the Λ is much tighter bound there, so a deviation from the free Λ lifetime is expected.

There is a strong correlation between the R_3 ratio (defined as the ratio between the charged two-body decay mode to all charged decay modes) and the binding energy. If one uses new model constraints [18] and compares to the world average including recent STAR measurements [34] one gets a value very consitent with the Λ separation energy discussed before. Interestingly, when only the new preliminary value of the STAR Collaboration is used one rather gets a value for B_Λ below 100 keV, which is consistent with the preliminary result for B_Λ from the ALICE Collaboration.

3 Summary and Conclusion

Many new interesting results on (anti-)(hyper)nuclei have been presented recently. In particular nice is that a larger energy range is now available since the HADES Collaboration [40] joined the stage and STAR has large data sets at low and intermediate energy. A definite highlight is the first observation of anti-hyperhydrogen-4 by the STAR Collaboration [33].

The typically discussed production models, i.e. thermal and coalescence, are giving differently good description at different energies. Typically, both models give a rather good description. Using the current descriptions from theory the experimental results at small systems seem to slightly prefer the coalescence model [37, 38], whereas the canonical statistical model is significantly off [27].

The (average) lifetimes of all hypernuclei are significantly below the free Λ lifetime, which is expected for the mass $A = 4$ hypernuclei but not for the hypertriton. In that view, the "hypertriton puzzle" is not yet solved.

It is clear from all new results that more data and even more precise data can be expected in the next years by all involved experiments.

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