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MESON2016 – Concluding Remarks

Avraham Gal[1,⋆]

[1] *Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel*

Abstract. Several topics presented and discussed at MESON2016 are highlighted, including pentaquarks, dibaryons and meson-nuclear bound states.

1 Introduction

The scope of topics presented and discussed in MESON2016 is too broad to be covered in one concluding talk. I therefore selected a few central topics discussed in MESON2016 where my personal involvement helped making some meaningful remarks. These topics are Pentaquarks, Dibaryons, and Meson-Nuclear Bound States. I apologize to the many speakers whose presentations were not mentioned in this concluding talk.

2 Exotics: remarks on Pentaquarks

Regarding *pentaquarks*, it is appropriate perhaps to note that the $\mathcal{S} = -1$ $\Lambda(1405)$ resonance, defying a three-quark classification, was predicted in 1959 by Dalitz and Tuan as a $\bar{K}N$ quasibound state [1] five years *before* the term 'quark' was transformed by Gell-Mann from Fiction to Physics. A recent LQCD calculation confirms its $\bar{K}N$ hadronic structure [2] as opposed to a tightly bound genuine pentaquark. Indeed, the $\Lambda(1405)$ emerges naturally below the K^-p threshold in chiral EFT hadronic approaches [3], although as shown in Cieplý's talk [4] the *subthreshold* $\bar{K}N$ scattering amplitudes exhibit appreciable model dependence, with consequences for K^-pp quasibound-state searches.

A $\mathcal{S} = +1$ $\Theta^+(1530)$ pentaquark was claimed more than 10 years ago. Recent dedicated experimental searches have failed to confirm it, placing instead upper limits on its coupling to the KN channel [5]. It was argued that the Θ^+ might be formed copiously in nuclei by absorption on *two* nucleons, e.g. $K^+d \to \Theta^+p$ [6, 7] thereby resolving a long-standing puzzle, discussed in Friedman's talk [8], regarding the size and A dependence of K^+ nuclear cross sections at low energies.

The recent LHCb discovery of hidden-charm structures [9] has led to several serious attempts to interpret these in terms of pentaquark(s). As argued in Karliner's talk the relatively small width of order 40 MeV for $P_c(4550)$ supports a $\Sigma_c\bar{D}^*$ hadronic molecule structure of two quark clusters, rather than a tightly bound pentaquark; see Fig. 1 on next page. This $\Sigma_c\bar{D}^*$ hadronic molecule is apparently the lightest of several other predicted doubly-heavy hadronic molecules [10]. It was emphasized that this calls for a new rich meson-meson, meson-baryon and baryon-baryon heavy-flavor QCD spectroscopy. Other speakers too discussed various aspects of heavy-flavor Exotics, demonstrating that no clear consensus has yet been reached on this topic.

⋆e-mail: avragal@savion.huji.ac.il

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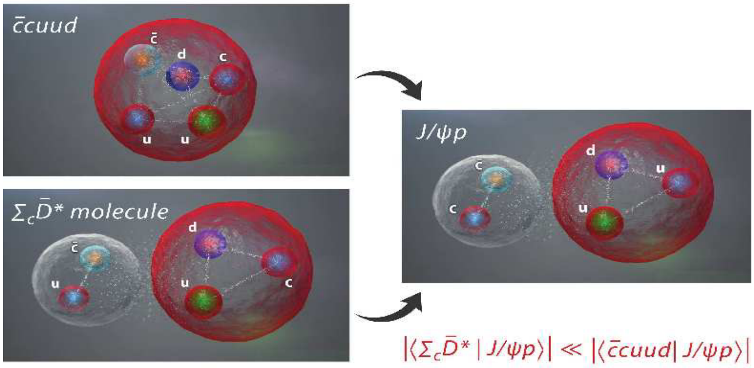

Figure 1. Left: two alternative visual descriptions of the LHCb hidden-charm pentaquark $P_c(4550)$ as a tightly bound $\bar{c}cuud$ pentaquark or as a $\Sigma_c\bar{D}^*$ hadronic molecule. Right: $P_c(4550) \to J/\psi + p$ decay channel which for a $\bar{c}cuud$ pentaquark implies a considerably larger width than reported. Figure adapted from Karliner's talk.

3 Exotics: remarks on Dibaryons

3.1 Nonstrange dibaryons

The only dibaryon for which good experimental evidence exists to date is the nonstrange $I = 0$ $J^P = 3^+$ $\mathcal{D}_{03}(2380)$, peaking ≈85 MeV below the ΔΔ threshold. The WASA-at-COSY experiments that established it, see Fig. 2, were ranked in Wilkin's obituary of COSY at MESON2016 a top no. 2 in COSY's impact list. The small width of $\mathcal{D}_{03}(2380)$, $\Gamma \approx 70$ MeV, less than even a single Δ width, was shown (on p. 479 in Ref. [14]) to follow from phase-space and quantum-statistics arguments.

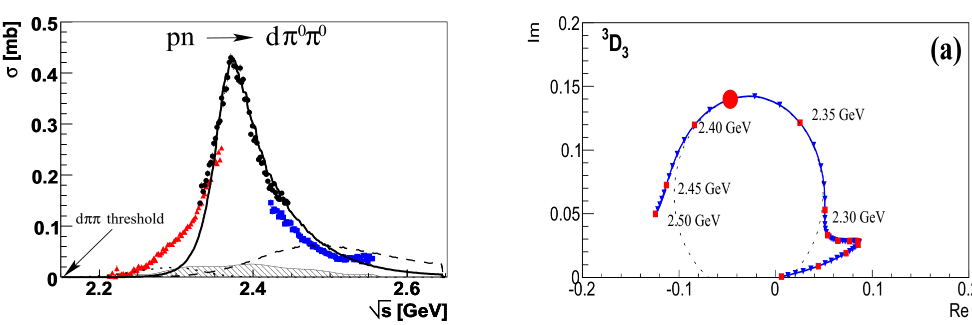

Figure 2. Evidence for the $\mathcal{D}_{03}(2380)$ dibaryon from WASA-at-COSY. Left: from $p + d \to d\pi^0\pi^0 + p_s$ [11]. Right: from the Argand diagram of the $^3D_3$ partial wave in np scattering [12], with full account of the recent measurement of the np analyzing power [13].

The large binding energy of $\mathcal{D}_{03}(2380)$ with respect to ΔΔ, exceeding by far the scale of nucleon separation energies in nuclei, does not mean it is a deeply bound dibaryon if one recalls the existence of a lower two-body channel, $\pi\mathcal{D}_{12}(2150)$, relative to which $\mathcal{D}_{03}(2380)$ resonates. Here, $\mathcal{D}_{12}(2150)$ stands for a near-threshold $N\Delta$ $I = 1$ $J^P = 2^+$ πNN quasibound state. Both $\mathcal{D}_{12}$ and $\mathcal{D}_{03}$, together with their $I \leftrightarrow S$ twins $\mathcal{D}_{21}$ and $\mathcal{D}_{30}$, were proposed by Dyson and Xuong [15] based on symmetry arguments, and have been considered subsequently in numerous quark-based works; and recently also in terms of 'meson assisted dibaryons' [14] in the hadronic basis [16, 17].

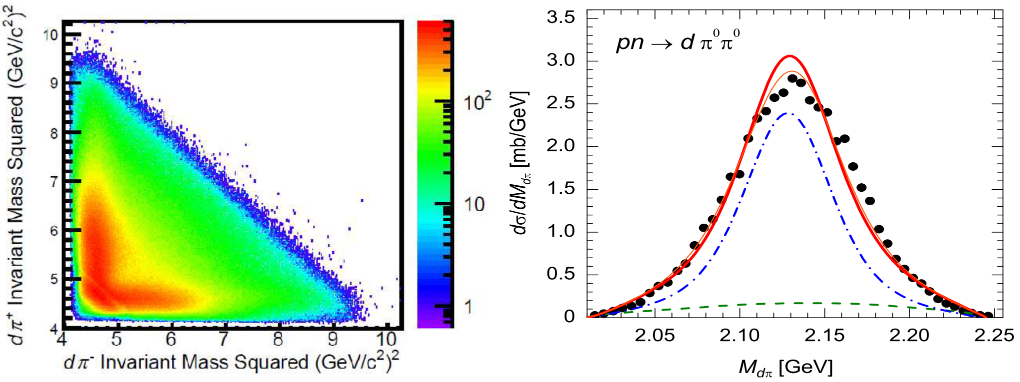

Figure 3. Left: $\mathcal{D}_{12}(2150)$ $N\Delta$ dibaryon signal in the Dalitz plot of $M^2_{d\pi^+}$ vs. $M^2_{d\pi^-}$ from a preliminary report on $\gamma d \to d\pi^+\pi^-$ measurements in the g13 experiment (CLAS Collaboration) at JLab [18]. Right: The $pn \to d\pi^0\pi^0$ WASA-at-COSY $M_{d\pi}$ distribution [11] and, in solid lines, as calculated [19] for two input parametrizations of $\mathcal{D}_{12}(2150)$. The dot-dashed line gives the $\pi\mathcal{D}_{12}(2150)$ contribution to the two-body decay of $\mathcal{D}_{03}(2380)$, and the dashed line gives a scalar-isoscalar σ-meson emission contribution.

The relevance of the $\mathcal{D}_{12}(2150)$ $N\Delta$ dibaryon to the physics of the $\mathcal{D}_{03}(2380)$ $\Delta\Delta$ dibaryon is demonstrated in Fig. 3 by showing, on the left panel, a $d\pi^\pm$ invariant-mass correlation near the $N\Delta$ threshold as deduced from preliminary CLAS data on the $\gamma d \to d\pi^+\pi^-$ reaction [18] and, on the right panel, a $d\pi$ invariant-mass distribution peaking near the $N\Delta$ threshold as deduced from the WASA-at-COSY $pn \to d\pi^0\pi^0$ reaction by which the $\mathcal{D}_{03}(2380)$ was discovered [11]. These preliminary CLAS data for $\gamma d \to d\pi^+\pi^-$ suggest a subthreshold $\mathcal{D}_{12}(2150)$ dibaryon with mass 2115±10 MeV and width 125±25 MeV [18], consistently with past deductions. The peaking of the $d\pi$ invariant-mass distribution in the $pn \to d\pi^0\pi^0$ reaction essentially at this $\mathcal{D}_{12}(2150)$ mass value suggests that the two-body decay modes of $\mathcal{D}_{03}(2380)$ are almost saturated by the $\pi\mathcal{D}_{12}(2150)$ decay mode, as reflected in the calculation [19] depicted in the right panel.

The success of *hadronic* model calculations [16, 17] to reproduce such $\mathcal{D}_{IS}$ dibaryon signals is consistent with the failure of recent quark-based calculations [20] to find tightly bound *hexaquarks* by using realistic color-spin hyperfine and color confinement quark-quark interactions. An hexaquark with quantum numbers identical to those of $\mathcal{D}_{03}$ lies at least 150 MeV above the $\Delta\Delta$ threshold, and this gap gets larger for other hexaquark candidates; a similar conclusion also holds for Jaffe's $\mathcal{S} = -2$ $I(J^P) = 0(0^+)$ $\mathcal{H}$ hexaquark [21]. This means that the proper degrees of freedom in the case of nonstrange dibaryons are nucleons, pions and Δ baryons, and that physical thresholds and p-wave pions must be realistically incorporated in future considerations of such dibaryons.

3.2 Strange dibaryons

Following recent searches for a $\bar{K}NN$ $I(J^P)=\frac{1}{2}(0^-)$ quasibound state (loosely termed K^-pp) in Frascati [22, 23], SPring-8 [24] and GSI [25, 26], Iwasaki reported in MESON2016 on dibaryon candidates from J-PARC Experiments E27 [27, 28] and E15 [29, 30], with binding energies given by

$$\text{deep}: \; B_{K^-pp}(\text{E27}) \approx 95 \text{ MeV}, \qquad \text{shallow}: \; B_{K^-pp}(\text{E15}) \approx 15 \text{ MeV}, \tag{1}$$

relative to the K^-pp threshold at 2370 MeV. To understand the possible origin of such radically different $\mathcal{S} = -1$ dibaryon candidates, it is instructive to look at the E27 $d(\pi^+, K^+)X$ small-angle missing-mass spectrum, Fig. 4(left), which indicates ≈22 MeV attractive shift of the $Y^*(1385 + 1405)$ unresolved quasi-free peak, consistently with the attraction calculated in the $I(J^P)=\frac{1}{2}(0^-)$ $\Lambda(1405)N$ s-wave channel that overlaps substantially with K^-pp [31]. Chirally motivated K^-pp calculations also suggest binding of order 20 MeV, as reviewed in Ref. [32], in rough agreement with the E15 $^3\text{He}(K^-, n)X$ near-threshold signal but not with the E27 deeply-bound signal shown in Fig. 4(right). The relatively shallow K^-pp binding persists in three-body calculations upon including the $\pi\Lambda N$ and $\pi\Sigma N$ lower-mass channels [33] which play only a secondary role in binding $\bar{K}$ mesons.

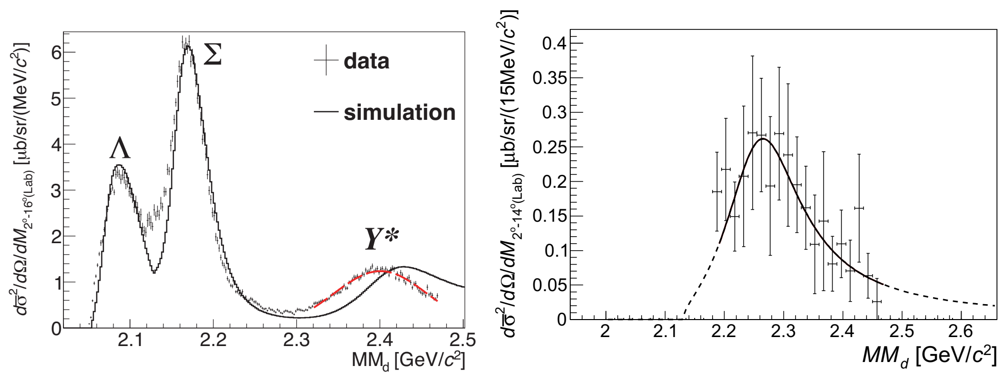

Figure 4. J-PARC E27 $d(\pi^+, K^+)X$ missing-mass spectra at $p_{\pi^+} = 1.69$ GeV/c. Left: small-angle K^+ inclusive quasi-free spectrum [27]. Right: $\Sigma^0 p$ decay branch of a pp coincidence spectrum [28].

The $\pi\Lambda N$–$\pi\Sigma N$ system, however, may benefit from sizable meson-baryon p-wave interactions, in terms of $\Delta(1232) \to \pi N$ and $\Sigma(1385) \to \pi\Lambda$–$\pi\Sigma$ strong-decay form factors, by aligning isospin and angular momentum to total $I(J^P)=\frac{3}{2}(2^+)$. Such a pion assisted dibaryon was studied in Ref. [34] by solving πYN coupled-channel Faddeev equations, thereby predicting a new $\mathcal{S} = -1$ dibaryon resonance $\mathcal{Y}_{\frac{3}{2}2^+}$ slightly below the $\pi\Sigma N$ threshold ($\sqrt{s_{\text{th}}} \approx 2270$ MeV). Adding a $\bar{K}NN$ channel hardly matters, since its leading $^3S_1$ NN component is Pauli forbidden. The E27 deeply bound broad signal at $\sqrt{s} \sim 2275$ MeV shown in Fig. 4(right) may then correspond to the production of such $\mathcal{Y}^+_{\frac{3}{2}2^+}$ in $\pi^+ + d \to \mathcal{Y}^+ + K^+$, followed by its decay to $\Sigma^0 + p$ [35]. We note that the $\mathcal{S} = -1$ $\mathcal{Y}_{\frac{3}{2}2^+}(2275)$ dibaryon may have good overlap with $^5S_2$, $I = \frac{3}{2}$ $\Sigma(1385)N$ and $\Delta(1232)Y$ dibaryon configurations, the lowest threshold of which, that of $\Sigma(1385)N$, is only ∼50 MeV above the $\pi\Sigma N$ threshold.

Other possible search reactions that are isospin selective as far as the final $\mathcal{Y} \to \Sigma N$ decay is concerned are

$$\pi^\pm + d \to \mathcal{Y}^{++/-} + K^{0/+}, \qquad p + p \to \mathcal{Y}^{++} + K^0, \tag{2}$$

in which the produced dibaryon $\mathcal{Y}$ decays to a ΣN final charge state which is uniquely $I = \frac{3}{2}$, viz. $\mathcal{Y}^{++/-} \to \Sigma^\pm + p(n)$. The pp reaction has been reported by the HADES Collaboration at GSI [36], finding no $\mathcal{Y}$ dibaryon signal. It is not clear whether the pp experiments were able to resolve as small cross sections as 0.1 μb or less that are expected in production of $\mathcal{Y}$ dibaryon candidates [26].

3.3 Charmed dibaryons

Charmed, $C = +1$ dibaryons have also been predicted: (i) a $I(J^P)=\frac{1}{2}(0^-)$ dynamically generated DNN quasibound state at 3.5 GeV [37] reminiscent of the $\mathcal{S} = -1$ K^-pp; and (ii) a $I(J^P)=\frac{3}{2}(2^+)$ $\pi\Lambda_c N$ quasibound state below 3.4 GeV [38], analogous to the $\mathcal{S} = -1$ pion assisted dibaryon $\mathcal{Y}_{\frac{3}{2}2^+}$. The prediction of this charmed pion assisted dibaryon $C_{\frac{3}{2}2^+}(3370)$ is robust, since it depends little on the unknown $^3S_1$ $\Lambda_c N$ interaction. The $C_{\frac{3}{2}2^+}(3370)$ is likely to be the *lowest lying* charmed dibaryon. It could be searched with proton beams at GSI, and with pion beams in the high-momentum hadron beam line extension approved at J-PARC, viz.

$$(p + p) \text{ or } (\pi^+ + d) \rightarrow C^{+++} + D^-, \qquad C^{+++} \rightarrow \Sigma_c^{++}(2455) + p. \tag{3}$$

4 Meson-nuclear bound states

No meson-nuclear bound states have been firmly established so far. For K^- mesons, extrapolating from kaonic atoms [39] it is widely accepted that broad quasibound states exist [40]. K^+ mesons, in contrast, experience repulson in dense (nuclear) matter. This is naively explained by a mean-field treatment of $K^- \equiv s\bar{u}$ and $K^+ \equiv \bar{s}u$ mesons, arguing that a nonstrange antiquark/quark induces attraction/repulsion in dense matter. In the charmed sector, one would then expect *attraction* for $D^+ \equiv c\bar{d}$ and repulsion for $D^- \equiv \bar{c}d$ mesons. This is not borne out in a recent QCD sum-rule calculation, showing in Fig. 5(left) a *repulsive* mass shift in dense matter, as a function of the assumed value of the πN σ term, for *both* $D^\pm$ mesons [41]. Fig. 5(right) shows that an attractive D^+ mass shift is possible in principle, but only for unrealistically high values of the heavy-quark mass m_h. This result has also been explained in Ref. [42] using a constituent quark picture.

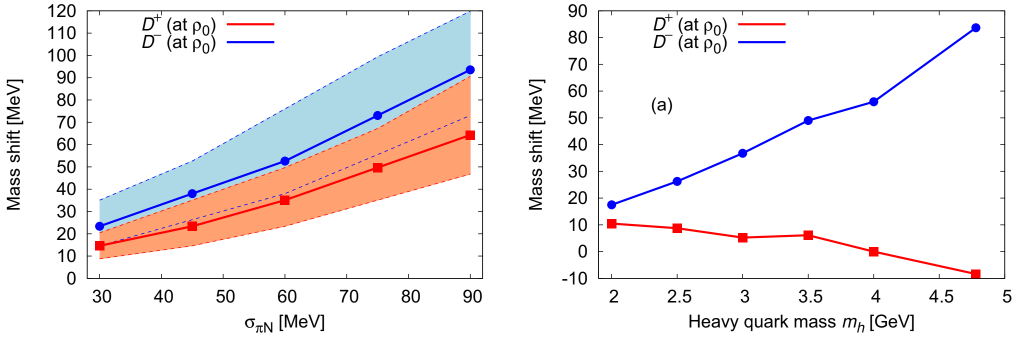

Figure 5. *D* meson mass shift in nuclear matter [41] vs. $\sigma_{\pi N}$ (left) and vs. the heavy quark mass m_h (right).

Turning to nonstrange and noncharmed meson-nuclear interactions discussed in MESON2016, Nanova reviewed recent ω and η' nuclear photoproduction experiments by the CBELSA/TAPS Collaboration which study the meson momentum dependence of the extracted meson-nucleus optical potential, suggesting that while the ω-nucleus potential is too absorptive to observe distinct quasibound states, the η'-nucleus potential is weakly absorptive [43] and sufficiently attractive [44] to motivate searches for η'-mesic nuclear states. Ongoing searches in ^{12}C(p,d) at GSI were discussed in Tanaka's talk. However, with $p_{\eta'}$ centered about ~1 GeV in the ELSA experiments, the optical potential derived for η' at rest depends on extrapolation from the lowest available value $p_{\eta'} \approx 275$ MeV/c down to threshold, where COSY-11 data on near-threshold meson production in pp collisions indicate a rather strong ηp attraction that is likely to support η-mesic nuclear states and a much weaker $\eta' p$ interaction [45], for the real part of which only a limit consistent with zero can be placed [46]. Citing from Wilkin's talk: "I would not put any money on bound η' in nuclei!". Within a QCD-inspired $\eta - \eta'$ mixing model [47], η'-nuclear attraction of roughly -40 MeV at saturation density as derived in the ELSA experiment [44] implies about -90 MeV for η attraction in nuclear matter, commensurate with the attraction expected in the ηN interaction model GW considered below. For these and for other reasons specified below, the following discussion is limited to η-nuclear quasibound states.

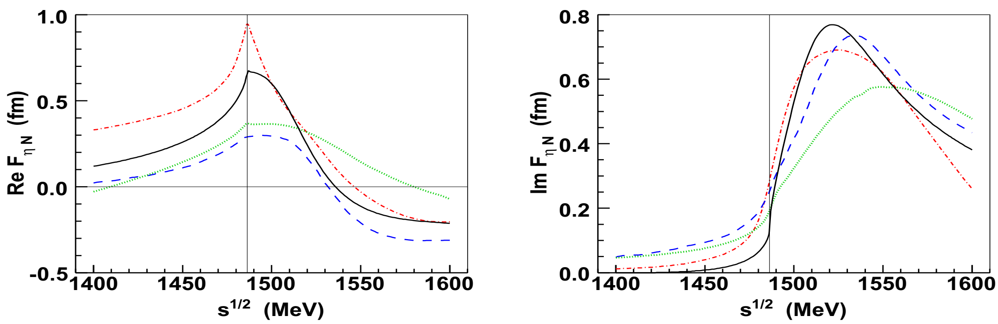

Figure 6. Real (left) and imaginary (right) parts of the ηN s-wave cm scattering amplitude $F_{\eta N}(\sqrt{s})$, compiled in Ref. [48] from several $N^*(1535)$ resonance coupled-channel models, in decreasing order of Re $a_{\eta N}$: GW [49], CS [50], MBM [51] and IOV [52]. The ηN threshold is marked by a thin vertical line.

The ηN near-threshold dynamics is governed by the $N^*(1535)$ resonance, introducing thereby appreciable model dependence in coupled-channel calculations of the s-wave scattering amplitude $F_{\eta N}(\sqrt{s})$, as seen in Fig. 6. Owing to the nearby $N^*(1535)$, both Re $F_{\eta N}$ and Im $F_{\eta N}$ decrease in all models steadily below threshold, which is where bound states are calculated. This decrease persists also in in-medium extensions $F_{\eta N}(\sqrt{s}, \rho)$ of the ηN scattering amplitude, suggesting that η-nuclear states are narrow. I know of no similar mechanism that would suggest as narrow η'-nuclear states.

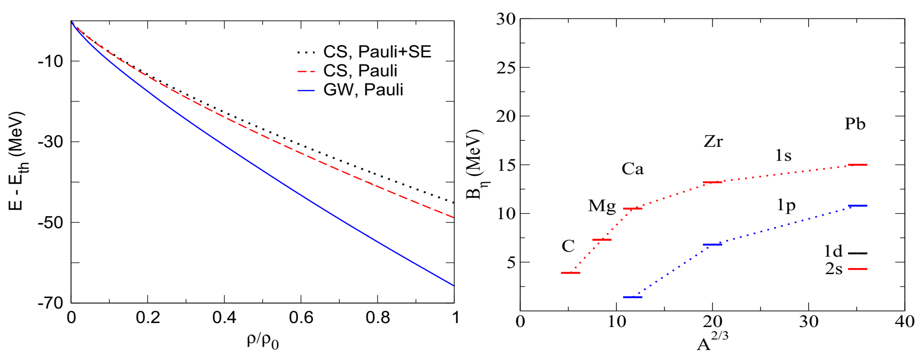

Figure 7. Left: Subthreshold energies probed in the $1s_\eta$-^{40}Ca bound state as a function of nuclear density, calculated self-consistently for in-medium ηN scattering amplitudes in models GW and CS used in Ref. [53]. Right: η-nuclear spectra [54] calculated self-consistently using the in-medium CS model NLO30$_\eta$ [50].

The subthreshold energy $\sqrt{s}$ and the nuclear density ρ, both serving in bound state calculations as arguments of the in-medium meson-nucleon scattering amplitude $F_{mN}(\sqrt{s},\rho)$, are tightly correlated as demonstrated in Fig. 7(left) within a particular η-nucleus calculation. This correlation imposes a self-consistent procedure in bound state calulations [48], as discussed here by Mareš.

A chart of η-nuclear bound states calculated self-consistently in the CS model is shown in Fig. 7(right). Since $\mathrm{Im}\,F_{\eta N}(\sqrt{s})$ is particularly small in model CS below threshold, see Fig. 6(right), the resulting η-nuclear widths are just a few MeV, and only somewhat larger in model GW. Bound states should definitely exist in ^{12}C and beyond, and beginning in ^{6}Li in model GW which according to Fig. 6(left) provides the strongest ηN attraction among the four models exhibited, Few-body calculations have also been reported recently using the ηN interaction models GW and CS. No bound state was found for ηd and for $\eta\,^{3}$He [55]. Calculations are underway for $\eta\,^{4}$He.

5 Summary and outlook

Several topics discussed in MESON2016 were picked up selectively in these Concluding Remarks, the common grounds of which is the rich spectroscopic variety that remains largely to be uncovered in hadronic systems. The impression gained at this Conference is that no consensus has been reached on the hidden-charm structures observed recently for mesons and for baryons in the energy range 2–5 GeV. In the absence of compelling arguments, or calculations classifying these in terms of genuine tetraquarks and pentaquarks, the only logical conclusion is that of hadronic-molecule underlying structure. For dibaryons too, highlighting recent experimental results from COSY (nonstrange) and J-PARC (strange), the evidence points to hadronic structure. Finally, we focused attention to the possible existence of observable η-nuclear quasibound states, which could be explored at GSI using (p,d) and in J-PARC using the (π^+,p) reaction on nuclear targets.

I would like to thank the Organizers of MESON2016 for trusting me in this unthankful job.

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