The $d^*(2380)$ dibaryon resonance width and decay branching ratios

A. Gal

Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel

Abstract

Attempts to reproduce theoretically the width $\Gamma_{d^*} \approx 80 \pm 10$ MeV of the $I(J^P) = 0(3^+) d^*(2380)$ dibaryon resonance established by the WASA-at-COSY Collaboration are discussed. The validity of associating the $d^*(2380)$ in quark-based models exclusively with a tightly bound $\Delta\Delta$ configuration is questioned. The $d^*(2380)$ width and decay branching ratios into $NN\pi\pi$, $NN\pi$ and $NN$ final states are studied within the Gal-Garcilazo hadronic model in which the $d^*(2380)$ is a $\pi N\Delta$ resonance embedded in the $NN\pi\pi$ continuum some 80 MeV below the $\Delta\Delta$ threshold. In particular, predictions are made for the branching ratios of the unobserved yet $d^*(2380)$ decays which are suppressed in a purely-$\Delta\Delta$ dibaryon model. Comments are also made on a possible connection of the ABC effect observed in the $pn \rightarrow d^* \rightarrow d\pi^0\pi^0$ resonance reaction to the $d^*(2380)$ dibaryon.

Keywords: pion-assisted dibaryons; $d^*(2380)$ $\Delta\Delta$ dibaryon

1. Introduction

The WASA-at-COSY Collaboration observed a relatively narrow peak, $\Gamma_{d^*} \approx 70$ MeV, about 80 MeV below the $\Delta\Delta$ threshold in the $pn \rightarrow d\pi^0\pi^0$ reaction [1]. This peak, shown on the left panel of Fig. 1, was identified with the $I(J^P)=0(3^+) D_{03}(2350)$ $\Delta\Delta$ dibaryon predicted in 1964 by Dyson and Xuong [2]. The $I = 0$ isospin assignment follows from the isospin balance in $pn \rightarrow d\pi^0\pi^0$, and the $J^P = 3^+$ spin-parity assignment follows from the measured deuteron angular distribution. The $d^*(2380)$ was also observed in $pn \rightarrow d\pi^*\pi^0$, with cross section consistent with that measured in $pn \rightarrow d\pi^0\pi^0$ [3], and studied in several other related $pn \rightarrow NN\pi\pi$ reactions [4, 5, 6]. Recent

\* corresponding author: Avraham Gal, avragal@savion.huji.ac.il

Preprint submitted to Physics Letters B

August 4, 2018
measurements of \(pn\) scattering and analyzing power \cite{7} have led to the \(pn\ \mathbf{3D}_1\) partial-wave Argand diagram shown on the right panel of Fig.\,1\cite{1} supporting the \(d^*(2380)\) dibaryon resonance interpretation.

The mass of a possible \(I(J^P)=(0^+)\ \Delta\Delta\) dibaryon has been the subject of many quark-based calculations \cite{8} but its width received little attention, and that \cite{9,10} only since the discovery of the \(d^*(2380)\). The term ‘quark-based’ does not necessarily mean that the resulting \(d^*(2380)\) is of a purely hexaquark structure. In fact, a recent quark-model study of spatially symmetric \(L=0\) \(6q\) states finds that the \(I(J^P)=(0^+)\) hexaquark several hundreds of MeV above the \(\Delta\Delta\) threshold \cite{11}. It is by adding potentially double-counting meson exchanges, e.g. a scalar-isoscalar \(\sigma\) meson, and applying resonating group methods (RGM), that quark-based calculations generate a tightly bound and compact \(\Delta\Delta\) dibaryon.

The \(d^*(2380)\) was also studied recently \cite{12,13} within a \(\pi D_{12}-\Delta\Delta\) coupled-channels \(\pi N\Delta\) hadronic model, using \(\pi N\) and \(N\Delta\) pairwise interactions each of which produces its own resonance: the \(I(J^P)=(1^+)\ \Delta\Delta\) baryon, and the \(I(J^P)=1(2^+)\ D_{12}(2150)\) dibaryon resonance generated by solving \(NN\pi\) three-body Faddeev equations. The \(d^*(2380)\) \(S\)-matrix pole in this model is embedded in the \(NN\pi\) continuum, about midway between the corresponding two-body thresholds, giving rise to a two-component structure: a resonance with respect to the lower \(\pi D_{12}\) threshold and a tightly bound state with respect to the upper \(\Delta\Delta\) threshold. This coupled-channels structure of the \(d^*(2380)\) dibaryon is absent in quark-based \(\Delta\Delta\) dibaryon models.

In this note, we discuss the role of the lower channel \(\pi D_{12}\) in explaining the \(d^*(2380)\) width \(\Gamma_{d^*}\approx 70\) MeV \cite{1} which is considerably smaller than twice the width of a single \(\Delta\) baryon, \(\Gamma_\Delta\approx 115\) MeV. It is shown in the next section that the \(d^*(2380)\) width would have been even smaller than its observed value, were it not restrained by the effect of the \(\pi D_{12}\) channel. In a subsequent section we discuss in some detail the \(d^*(2380)\) partial decay widths and decay branching ratios in comparison to those deduced from experiment \cite{14}. Predictions are made in particular for the \(d^*(2380)\rightarrow NN\pi\) partial decay widths which are suppressed to leading order within a \(\Delta\Delta\) single-channel description of the \(d^*(2380)\). We also comment on a possible connection of the ABC effect observed in \(pn\rightarrow d^*np\) \cite{15} to the \(d^*(2380)\) dibaryon.

2. Is the \(d^*(2380)\ \Delta\Delta\) dibaryon a compact or extended object?

Assuming a quasibound \(\Delta\Delta\) configuration for the \(d^*(2380)\) dibaryon, the phase space for a given \(J\rightarrow N\pi\) decay \((J=1,2)\) to occur independently of the other decay is reduced by binding: \(M_\Delta=1232\Rightarrow 1232-B_{\Delta\Delta}/2\) MeV, where \(B_{\Delta\Delta}=2\times 1232-2380=84\) MeV is the binding energy of the two \(\Delta\)s. This reduces the \(\Delta\) free-space width, \(\Gamma_\Delta\approx 115\) MeV \cite{16,17}, to 81 MeV using Eq.\,(3) below. However, this simple estimate is incomplete, as realized recently also by Niskanen \cite{18}, since neither of the two \(\Delta\)s is at rest within such a deeply bound \(\Delta\Delta\) state. To take account of the \(\Delta\Delta\) momentum distribution, we evaluate the bound-\(\Delta\) decay width \(\Gamma_{\Delta\rightarrow N\pi}(s_\Delta)\) over the \(\Delta\Delta\) bound-state momentum-space wavefunction squared,

\[\Gamma_{\Delta\rightarrow N\pi}\equiv \langle \Psi' (p_{\Delta\Delta}) | \Gamma_{\Delta\rightarrow N\pi}(\sqrt{s_\Delta}) | \Psi(p_{\Delta\Delta}) \rangle \approx \Gamma_{\Delta\rightarrow N\pi}(\sqrt{s_\Delta}),\]

(1)

with \(s_\Delta\) the invariant energy squared and its average bound-state value \(\sqrt{s_\Delta}\) defined by

\[s_\Delta = (1232-B_{\Delta\Delta}/2)^2 - p_{\Delta\Delta}^2, \quad \sqrt{s_\Delta} = (1232-B_{\Delta\Delta}/2)^2 - p_{\Delta\Delta}^2.\]

(2)

in terms of a \(\Delta\) bound-state variable momentum \(p_{\Delta\Delta}\) and its r.m.s. value \(p_{\Delta\Delta} \equiv (p_{\Delta\Delta}^2)^{1/2}\).

In Table\,1 we list values of \(\sqrt{s_\Delta}\) and the associated in-medium decay-pion momentum \(\vec{q}_{\Delta\rightarrow N\pi}\) for several representative values of the r.m.s. radius \(R_{\Delta\Delta} \equiv \langle r_{\Delta\Delta}^2 \rangle^{1/2}\) of the bound \(\Delta\Delta\) wavefunction, obtained from Eq.\,(1) by using the equality sign in the uncertainty relationship \(P_{\Delta\Delta} R_{\Delta\Delta} \geq 3/2\), in units of \(h=c=1\). Listed also are values of the in-medium single-\(\Delta\) width \(\Gamma_{\Delta\rightarrow N\pi}\), obtained from the empirical \(\Delta\)-decay momentum dependence

\[\Gamma_{\Delta\rightarrow N\pi}(\vec{q}_{\Delta\rightarrow N\pi}) = \gamma \frac{q_{\Delta\rightarrow N\pi}^2}{q_0^4 + \vec{q}_{\Delta\rightarrow N\pi}^4},\]

(3)

with \(\gamma = 0.74\) and \(q_0 = 159\) MeV \cite{13}. By relating \(\vec{q}_{\Delta\rightarrow N\pi}\) in this expression to \(\sqrt{s_\Delta}\) of Eq.\,(2) in the same way as in free space, it is implicitly assumed here that this empirical momentum dependence provides a good approximation
Table 1: Values of √s∆ as a function of R∆∆, using P∆AR∆ = 1/2 in Eq. (2), values of the corresponding decay-pion momentum q∆→Nπ, values of Γ∆→Nπ from Eq. (3) and of Γ∆∆→NNππ ≃ 5/3 Γ∆→Nπ.

| R∆∆ (fm) | √s∆ (MeV) | q∆→Nπ (MeV) | Γ∆→Nπ (MeV) | Γ∆∆→NNππ (MeV) |
|----------|------------|--------------|--------------|-----------------|
| 0.6      | 1083       | 38.3         | 1.6          | 2.6             |
| 0.7      | 1112       | 96.6         | 19.3         | 32.1            |
| 0.8      | 1131       | 122.0        | 33.5         | 55.8            |
| 1.0      | 1153       | 170.4        | 67.4         | 112.3           |
| 1.5      | 1174       | 177.9        | 73.2         | 122.0           |

also for off-shell ∆s. Finally, The last column of the table lists values of Γ∆∆→NNππ obtained by multiplying Γ∆→Nπ by two, for the two ∆s, while applying to one of them the isospin projection factor 2/3 introduced in the Gal-Garcilazo hadronic model [12, 13] to satisfy the quantum statistics requirements in the leading final NNππ decay channels.

The large spread of Γ∆∆→NNππ width values exhibited in the table, all of which are much smaller than the 162 MeV obtained by ignoring in Eq. (2) the bound-state momentum distribution, demonstrates the importance of this momentum contribution. It is seen that a compact d∗(2380) with values of R∆∆ between 0.6 to 0.8 fm is incompatible with the experimental value Γd∗(2380) = 80±10 MeV from WASA-at-COSY and SAID [7] even upon adding a non-pionic partial width Γ∆∆→NN ≃ 10 MeV [15]. In particular, R∆∆ = 0.76 fm from the quark-based model of Ref. [19], as shown on the l.h.s. panel of Fig. 2, leads to an unacceptably small value of about 47 MeV for the width. This drastic effect of momentum dependence is missing in quark-based decay-width calculations of a single ∆∆ configuration, e.g. Ref. [10], which would underestimate considerably the d∗(2380) width once the momentum distribution of a tightly-bound and compact ∆∆ is accounted for.

The preceding discussion of the d∗(2380) width suggests that the quark-based model’s finding of a tightly bound ∆∆ s-wave configuration is in conflict with the observed width. Fortunately, the hadronic-basis calculations mentioned in the Introduction offer resolution of this insufficiency by adding to the tightly bound and sub-fm compact

1This is an upper bound, given that the equality sign was used in the uncertainty relationship. Using an infinite square well of radius 1.43 fm that gives R∆∆ = 0.76 fm in the g.s., one gets a value of 27 MeV instead of 47 MeV for Γ∆∆→NNππ

Figure 2: Left: a d∗(2380) ∆∆ wavefunction with r.m.s. radius R∆∆ = 0.76 fm from quark-based RGM calculations [19]. Right: The pn → dππ0 WASA-at-COSY Mππ invariant-mass distribution [1] and, in solid lines, as calculated [24] for two input parametrizations of D12(2150). The dot-dashed line gives the πD12(2150) contribution to the two-body decay of the d∗(2380) dibaryon, and the dashed line gives a σ-meson emission contribution.

The preceding discussion of the d∗(2380) width suggests that the quark-based model’s finding of a tightly bound ∆∆ s-wave configuration is in conflict with the observed width. Fortunately, the hadronic-basis calculations mentioned in the Introduction offer resolution of this insufficiency by adding to the tightly bound and sub-fm compact
ΔΔ component of the \(d^*(2380)\) dibaryon’s wavefunction a \(pNΔ\) resonating component dominated asymptotically by a \(p\)-wave pion attached loosely to the near-threshold \(NΔ\) dibaryon \(D_{12}\) with size about 1.5–2 fm. Formally, one can recouple spins and isospins in this \(πD_{12}\) system, as demonstrated in the Appendix, so as to assume an extended ΔΔ-like object. This explains why the preceding discussion of \(Γ_{d^*→NΔππ}\) in terms of a ΔΔ constituent model required a size larger than provided by corresponding quark-based RGM calculations [10]. We recall that the πNΔ model [12,13] does reproduce the observed width of the \(d^*(2380)\) dibaryon resonance. The relevance of the \(D_{12}(2150)\ NΔ\) dibaryon to the physics of the \(d^*(2380)\) resonance is also demonstrated on the r.h.s. of Fig. 2 by showing a \(dπ\) invariant-mass distribution peaking near the \(N\Δ\) threshold as deduced from the \(pn \rightarrow dπ^0π^0\) reaction by which the \(d^*(2380)\) was discovered [1]. This peaking, essentially at the \(D_{12}(2150)\) mass value, suggests that the \(πD_{12}\) two-body channel plays an important role in the decay modes of the \(d^*(2380)\) dibaryon, as reflected in the calculation of Ref. [20] depicted in the figure. The width of this invariant-mass distribution, nevertheless, agrees roughly with \(Γ_{d^*}(2380)\)≈80±10 MeV irrespective of the underlying decay mechanism.

To end this discussion of the two-channel structure of the \(d^*(2380)\) dibaryon resonance, we mention the ABC effect [21] which has been debated extensively in the context of the \(d^*(2380)\) dibaryon resonance [8]. For a recent study see Ref. [15]. Here, one observes a pronounced low-mass enhancement at \(M_{d^*π} \sim 0.3\) GeV in the \(π^0\) invariant mass distribution of the \(pn \rightarrow dπ^0π^0\) fusion reaction at \(√s = 2.38\) GeV. Realizing that the decay pions from a \(d^*(2380)\) compact ΔΔ component have particularly low momenta, we compute \(M_{d^*π} = 314\) MeV/c by using the value \(Γ_{Δ→Nπ} = 113.6\) MeV/c, corresponding to \(R_{πΔ} = 0.76\) fm from the quark-based calculations of Ref. [19]. The ABC enhancement appears not to arise in the \(pn \rightarrow pπ^0π^0\) non-fusion reaction, apparently because the outgoing quasi-free nucleons manage to affect the \(Δ \rightarrow Nπ\) decay spectra more readily than when bound in the deuteron. Furthermore, it was found in Ref. [15] that to reproduce the shape of the \(M_{d^*π}\) distribution relative to the ABC enhancement, a form factor of size approximately 2 fm is required. This would correspond in the present two-channel approach roughly to the size of the resonating π\(D_{12}\) component of the \(d^*(2380)\) dibaryon. More work is needed to substantiate these suggestions.

3. \(d^*(2380)\) partial decay widths and branching ratios

Here we evaluate the \(d^*(2380)\) partial decay widths and branching ratios (BR). Various pieces of experimental and theoretical input to the \(d^*(2380)\) production and decay data are incorporated in this evaluation as follows.

1. A value of \(Γ_{d^*tot}^{d^*} = 75\) MeV was adopted for the \(d^*(2380)\) total width to allow direct comparison with the analysis of Ref. [14]. This value is close to \(Γ_{d^*tot}^{d^*} = 70\) MeV derived from the observed \(pn \rightarrow dπ^0π^0\) resonance shape [1], and is within the range of values \(Γ_{d^*tot}^{d^*} = 80 \pm 10\) MeV determined by the SAID analysis of the WASA-at-COSY recent measurements of polarized \(d\) elastic scattering around the \(d^*(2380)\) resonance [7].

2. \(nn\) partial decay widths between 9 to 11 MeV were used for \(Γ_{NN}^{d^*}\), corresponding to BR between 0.12 and 0.15, in agreement with \(Γ_{NN}^{d^*}/Γ_{tot}^{d^*} = 0.12 \pm 0.03\) from the SAID determination [7] and with the value 0.15 extracted from the \(pn\) \(D_3\) Argand diagram shown in Fig. 1. The actual choice of \(Γ_{NN}\) is described in item 5 below.

3. A \(d^*(2380)\) resonance peak value of \(σ(pn \rightarrow d^* \rightarrow dπ^0π^0) = 240\) μb was assumed, following Ref. [14], to determine the product \(Γ_{tot}^{d^*}/Γ_{tot}^{d^*}\), and hence the value of \(Γ_{d^*ππ}^{d^*}\). For \(Γ_{d^*ππ}^{d^*}\) we multiplied \(Γ_{d^*πτ}^{d^*}\) by 1.83 [10], close to the pure isospin limit of 2, and followed the later work also to obtain \(Γ_{d^*πτ}^{d^*}\). The obtained value of \(Γ_{d^*πτ}^{d^*}\) was then multiplied by the same factor 1.83 as above to get the isoscalar part of \(Γ_{d^*πτ}^{d^*}\). With these values, the summed isoscalar part of \(Γ_{NNNN}^{d^*}\) amounts to 5.77×\(Γ_{d^*πτ}^{d^*}\). Note that nowhere in this derivation have we relied on the quark-based model work [10] total decay width \(Γ_{NNNN}^{d^*}\), with which, according to the discussion in Sect 2 we disagree.

4. To get the isovector part of \(Γ_{NNNN}^{d^*}\), which is not related directly by isospin to the isoscalar part, the summed isoscalar part of \(Γ_{NNNN}^{d^*}\), plus \(Γ_{NNNN}^{d^*}\), plus \(Γ_{NN}^{d^*}\), were subtracted from \(Γ_{tot}^{d^*}\). As for \(Γ_{NNNN}^{d^*}\) it was extracted in a model-dependent way discussed below from the \(πD_{12}\) component of \(d^*(2380)\) by using a BR \(Γ_{D_{12}}^{d^*}/Γ_{tot}^{d^*} \approx 0.18\), taken from the Argand diagram of the \(NN^1D_3\) partial wave in the SAID SP07 fit [16].

5. The dependence of the isovector part of \(Γ_{NNNN}^{d^*}\) on \(Γ_{NN}^{d^*}\) was used to choose a value for \(Γ_{NN}^{d^*}\) (see item 2 above) so as to reproduce the \(d^*(2380)\) resonance peak value of \(σ(pn \rightarrow d^* \rightarrow ppp\bar{n}π^0) \approx 100 \pm 10\) μb [5,14].
The $d^*(2380)$ partial decay widths (in MeV) and the corresponding BR (in percents) derived using these specifications are listed in Table 2 within (i) a pure $\Delta\Delta$ model ($\alpha = 1$), (ii) a pure $\pi\Delta_1$ model ($\alpha = 0$), and (iii) within a $d^*(2380)$ $\Delta\Delta$–$\pi\Delta_1$ mixing model ($\alpha = \frac{\pi}{4}$). The $\Delta\Delta$ decay fraction $\alpha$ is defined by Eq. (4) below. In this mixing model, the $d^*(2380)$ resonance consists of a superposition of inner $\Delta\Delta$ and outer $\pi\Delta_1$ (2150) components. The $NN\pi\pi$ decays from these two components involve quite different portions of phase space, and their associated widths add up incoherently. For the $NN\pi\pi$ decay width of the compact $\Delta\Delta$ component we chose a value of $\Gamma_\alpha = 44$ MeV, in between the values listed in Table 1 for $R_{\Delta\Delta} = 0.7$ and 0.8 fm. A corresponding value of $\Gamma_\alpha = 100$ MeV, inspired by the $\Delta\Delta_1$ (2150) total width of 120 MeV derived by solving the appropriate $\pi N N$ Faddeev equations [12, 13], from which we subtracted $\approx 20$ MeV for the $NN$ decay mode, was chosen for the $\pi\Delta_1$ (2150) asymptotic component. Assigning $NN\pi\pi$ decay fractions $\alpha$ and $1 - \alpha$, respectively, we solved the equation

$$a\Gamma_\alpha + (1 - a)\Gamma_\alpha = \Gamma_{NN\pi\pi}^\text{\alpha},$$

(4)

With $\Gamma_{NN\pi\pi}^\alpha \approx 10$ MeV, and expecting $\Gamma_{NN\pi\pi}^{\alpha} \approx 5$ MeV, we estimate $\Gamma_{NN\pi\pi}^{\alpha} = 60$ MeV. The value of $\alpha$ that solves this equation is $\alpha = \frac{\pi}{4}$. Future hadronic calculations should tell how good this representative value of $\alpha$ is. The partial decay widths and BR resulting in this mixing version are listed in Table 2 under the heading $\alpha = \frac{\pi}{4}$.

| Final state | $\Delta\Delta$ ($\alpha = 1$) | $\pi\Delta_1$ ($\alpha = 0$) | Mixed ($\alpha = \frac{\pi}{4}$) | $\exp.[14]$ |
|-------------|-------------------------------|-----------------------------|---------------------------------|------------|
| $d^0 n^0 p^0$ | 9.3                           | 12.4                        | 7.6                            | 10.1       |
| $d^0 n^0 p^0$ | 17.0                          | 22.7                        | 14.0                           | 18.6       |
| $p n^0 n^0$ | 9.7                           | 12.9                        | 7.9                            | 10.5       |
| $p n^0 n^0$ | 5.5                           | 5.5                         | 2.9                            | 3.9        |
| $N N\pi$ | –                             | –                           | 11.5                           | 15.4       |
| $N N\pi$ | 9                             | 12                          | 11                             | 14.7       |
| Total | 75                            | 100                         | 75                             | 100        |

Comparing the BR obtained in the three model versions specified by their value of the $\Delta\Delta$ fraction $\alpha$ with those derived from experiment in Ref. 14 and listed in the last column of Table 2 one notes the similarity between the BR obtained in a purely $\Delta\Delta$ model ($\alpha = 1$) and those derived from experiment. In fact, this similarity is somewhat fortuitous because all three model versions were designed to reproduce input values of the $d^*$ peak cross sections: $\sigma(p n \to d^* \to d^0 n^0 p^0) = 240 \mu b$ and $\sigma(p n \to d^* \to p p n^0 n^0) \approx 100 \pm 10 \mu b$ [14], thereby agreeing also for the rest of the $p n \to d^* \to NN\pi\pi$ cross sections. The three model versions figuring in Table 2 differ essentially only in their $NN\pi\pi$ BR which in the purely $\Delta\Delta$ model ($\alpha = 1$) is close to zero [24]. The $NN\pi$ partial decay width and BR listed for the purely $\pi\Delta_1$ model ($\alpha = 0$) were normalized to a total $d^*$ pionic width of 75–11=64 MeV. The relatively high value of $=15\%$ for the obtained BR is excluded by a recent determination of a $\leq 9\%$ upper limit [25]. In contrast, a value of the $NN\pi\pi$ BR smaller by almost a factor of two was obtained, by applying the $\pi\Delta_1$ decay fraction ($1 - \alpha$) to the $NN$ partial decay width $\Gamma_{NN\pi\pi}^{\alpha} = 0.18 \times 120$ MeV, in the specific mixing model version listing in Table 2.

How robust are the BR results shown for the $\Delta\Delta$–$\pi\Delta_1$ coupled channels scheme in Table 2? The listed BR are based on assuming a value $\Gamma_{NN\pi\pi}^{\alpha} = 10$ MeV. A $\pm 10\%$ variation of this value results in a $\pm 50\%$ variation in the cross section $\sigma(p n \to d^* \to p p n^0 n^0)$ away from its initially assumed value which can be restored by a $\pm 10\%$ variation in $\sigma(p n \to d^* \to d^0 n^0)$ away from its initially assumed value. We conclude that the partial decay widths and BR listed in Table 2 for a mixing parameter $\alpha = \frac{\pi}{4}$ have uncertainties of up to 10%, except for those for the $NN\pi\pi$ decay mode which depend only on the assumed value of $\alpha$.

Next we allow $\alpha$ to vary by replacing the value of $\Gamma_\alpha = 44$ MeV that served as input through Eq. (4) to derive the value of $\alpha = \frac{\pi}{4}$ in use in Table 2 by representative neighboring values 40 and 50 MeV. The resulting values of $\alpha$ are
\[ \alpha = \frac{3}{5} \text{ and } \frac{3}{2}, \text{ respectively, leading to the following uncertainty estimate for the } NN\pi \text{ decay mode:} \]

\[ \sigma(pn \rightarrow d^* \rightarrow NN\pi) = 178^{+29}_{-35} \mu b, \quad \frac{\Gamma_{NN\pi}^d}{\Gamma_{NN\pi}^t} \approx 6.2^{+1.0}_{-1.9} \text{ MeV}, \quad \frac{\Gamma_{NN\pi}^d}{\Gamma_{tot}^d} \approx 8.3^{+1.3}_{-2.5} \%. \quad (5) \]

Note that in addition to the \( NN\pi \) partial decay width \( \Gamma_{NN\pi}^d \) and branching ratio \( \Gamma_{NN\pi}^d/\Gamma_{tot}^d \), with central values as given already in Table 2, we have also provided here a cross-section estimate for \( \sigma(pn \rightarrow d^* \rightarrow NN\pi) \), with estimated uncertainties, to compare directly with the experimental upper limit of 180 \( \mu b \) \cite{25}. Given these uncertainties, the \( NN\pi \) production cross section could be as low as \( \sim 120 \mu b \), comfortably below the reported upper limit.

4. Conclusion

The \( d^*(2380) \) is the most promising dibaryon candidate at present, supported by systematic studies of its production and decay in recent WASA-at-COSY experiments \cite{8}. In most theoretical works, beginning with the 1964 Dyson-Xuong prediction \cite{2}, it is assigned as a \( \Delta\Delta \) quasibound state. Given the small width \( \Gamma_{d^*(2380)} = 80 \pm 10 \text{ MeV} \) with respect to twice the width of a free-space \( \Delta \), \( \Gamma_\Delta \approx 115 \text{ MeV} \), its location far from thresholds makes it easier to discard a possible underlying threshold effect. However, as argued in this work, the observed small width is much larger than what two \text{deeply bound} \( \Delta \) baryons can yield upon decay. The \( d^*(2380) \) therefore cannot be described exclusively by a \( \Delta\Delta \) component. A complementary quasi two-body component is offered in the \( \pi N \Delta \) three-body hadronic model of Refs. \cite{12,13} by a \( \pi D_{12} \) channel, in which the \( d^*(2380) \) resonates. The \( D_{12} \) dibaryon stands here for the \( I(J^P) = 1(2^+) \Delta N \) near-threshold system that might or might not possess a quasibound state \( S \)-matrix pole. It is a loose system of size typically 1.5–2 fm, as opposed to the compact \( \Delta\Delta \) component of size 0.5–1 fm. It was pointed out how the ABC low-mass enhancement in the \( \pi^0\pi^0 \) invariant mass distribution of the \( pn \rightarrow d\pi^0\pi^0 \) fusion reaction at \( \sqrt{s} = 2.38 \text{ GeV} \) might be associated with the small size of the \( \Delta\Delta \) component. Furthermore, we have shown how to determine the relative weight of these two components by fitting to the total \( d^*(2380) \) width, thereby deriving \( d^* \) partial decay widths and branching ratios that agree with experiment \cite{14}. A new element in the present derivation is the ability, through the \( \pi D_{12} \) channel, to evaluate the \( d^* \rightarrow NN\pi \) decay width and BR. Our prediction is for a BR of order 8%, considerably higher than that obtained for a quark-based purely \( \Delta\Delta \) configuration \cite{24}, but consistently with an upper limit of \( \lesssim 9\% \) determined recently by the WASA-at-COSY collaboration \cite{25}. A precise measurement of this decay width and BR will provide a valuable constraint on the \( \pi D_{12} \);\( \Delta\Delta \) mixing parameter.

Acknowledgments

Special thanks are due to Heinz Clement for stimulating exchanges on the physics of dibaryons \cite{8}, and to Maria Platonova on the \( \pi D_{12} \) interpretation of the \( d^*(2380) \) \cite{20}.

Appendix: Equivalence of isospin bases

Starting with a \( D_{12} \odot \pi \) structure of \( d^*(2380) \), we recall that \( D_{12} \) stands for a near-threshold \( \Delta N \) dibaryon, where \( \Delta \) is a \( P_{33} N\pi \) resonance, and recouple in isospace:

\[ \left\{ [(N_1 \odot \pi_1)_2 \odot N_2]_{D_{12}} \odot \pi_2 \right\}_{I=0} \rightarrow \left\{ [(N_1 \odot N_2)_{I_{D_{12}}} \odot \pi_1]_{I_{D_{12}}} \odot \pi_2 \right\}_{I=0}, \quad (6) \]

using the 6\( j \) orthogonal transformation with elements given by

\[ (-1)^{I_{NN}+1} \sqrt{4(2I_{NN}+1)} \begin{pmatrix} N_1 & N_2 & I_{NN} \\ I_{D_{12}} & \pi_1 & \frac{I_{NN}}{2} \end{pmatrix}, \quad (7) \]

where \( N_1 = N_2 = \frac{1}{2} \), and \( \pi_1 = \pi_2 = 1 \) denote the nucleons and pions isospins, respectively, and \( I_{D_{12}} = 1 \). The square of the \( I_{P_{33}} = 0 \) element is \( 2/3 \), and that of the \( I_{NN} = 1 \) element is \( 1/3 \). The \( I_{NN} = 0 \) projection factor \( 2/3 \) is the same as that considered in the Gal-Garcilazo hadronic model for the pionic decay modes of the \( \Delta\Delta \) component. Note that the \( NN\pi \) Faddeev calculation of \( D_{12} \) in Refs. \cite{12,13} was based on a single \( I_{NN} = 0 \), \( S_{NN} = 1 \) \( s \)-wave configuration.
thereby justifying the $I_{NN} = 0$ projection applied here. Note also that with $S_{NN} = 1$ and two $p$-wave pions, the angular momentum coupling needed for the $3^+ d^*(2380)$ is unique, with all individual components parallel to each other. Therefore we need to focus just on the isospin recoupling. Proceeding to recouple the state on the r.h.s. of Eq. (6),

$$\{(N_1 \otimes N_2)_{I_{NN}} \otimes \pi_1 \otimes \pi_2\}_{I=0} \rightarrow \{(N_1 \otimes N_2)_{I_{NN}} \otimes (\pi_1 \otimes \pi_2)_{I_{\pi}}\}_{I=0},$$  

where $I_{\pi} = I_{NN}$, we get $6j$ transformation elements identically 1,

$$(-1)^{I_{NN}} \sqrt{3(2I_{NN} + 1)} \begin{pmatrix} I_{NN} & \pi_1 & I_{D_{12}} \\ \pi_2 & 0 & I_{\pi} \end{pmatrix} = 1,$$  

irrespective of the value of $I_{NN} = I_{\pi}$. In Refs. [12, 13] we got the state on the r.h.s. of Eq. (8) by recoupling directly from a $\Delta \Delta$ configuration,

$$\{(N_1 \otimes \pi_1)_{1/2} \otimes (N_2 \otimes \pi_2)_{1/2}\}_{I=0} \rightarrow \{(N_1 \otimes N_2)_{I_{NN}} \otimes (\pi_1 \otimes \pi_2)_{I_{\pi}}\}_{I=0},$$  

using the $9j$ transformation

$$4 \sqrt{(2I_{NN} + 1)(2I_{\pi} + 1)} \begin{pmatrix} N_1 & \pi_1 & \frac{3}{2} \\ N_2 & \pi_2 & \frac{1}{2} \\ I_{NN} & I_{\pi} & 0 \end{pmatrix}$$  

which yields precisely the same $6j$ transformation elements as in Eq. (7). This establishes the equivalence of the $D_{12}\pi$ and $\Delta \Delta$ bases as far as the calculation of $\Gamma_{\Delta \Delta \rightarrow NN\pi\pi}$ branching ratios in section 3 is concerned.

References

[1] P. Adlarson et al. (WASA-at-COSY Collaboration), Phys. Rev. Lett. 106 (2011) 242302. See also the preceding reports: H. Clement et al. (CELSIUS-WASA Collaboration), Prog. Part. Nucl. Phys. 61 (2008) 276; M. Bashkanov et al. (CELSIUS/WASA Collaboration), Phys. Rev. Lett. 102 (2009) 052301.

[2] F.J. Dyson, N.-H. Xuong, Phys. Rev. Lett. 13 (1964) 815.

[3] P. Adlarson et al. (WASA-at-COSY Collaboration), Phys. Lett. B 721 (2013) 229.

[4] P. Adlarson et al. (WASA-at-COSY Collaboration), Phys. Lett. B 743 (2015) 325.

[5] P. Adlarson et al. (WASA-at-COSY Collaboration), Phys. Rev. C 88 (2013) 055208.

[6] G. Agakishiev et al., Phys. Lett. B 750 (2015) 184.

[7] P. Adlarson et al. (WASA-at-COSY Collaboration, SAID Data Analysis Center), Phys. Rev. C 90 (2014) 035204. See also P. Adlarson et al. (WASA-at-COSY Collaboration, SAID Data Analysis Center), Phys. Rev. Lett. 112 (2014) 202301.

[8] H. Clement, Prog. Part. Nucl. Phys. 93 (2017) 195.

[9] H. Huang, J. Ping, F. Wang, Phys. Rev. C 89 (2014) 034001, and references to earlier work listed therein.

[10] Y. Dong, F. Huang, P. Shen, Z. Zhang, Phys. Rev. C 94 (2016) 014037, and references to earlier work listed therein.

[11] W. Park, A. Park, S.H. Lee, Phys. Rev. D 92 (2015) 014037.

[12] A. Gal, H. Garcilazo, Phys. Rev. Lett. 111 (2013) 172301.

[13] A. Gal, H. Garcilazo, Nucl. Phys. A 928 (2014) 73.

[14] M. Bashkanov, H. Clement, T. Skorodko, Eur. Phys. J. A 51 (2015) 87.

[15] M. Bashkanov, H. Clement, T. Skorodko, Nucl. Phys. A 958 (2017) 129.

[16] R.A. Arndt, W.J. Briscoe, I.I. Strakovsky, R.L. Workman, Phys. Rev. C 76 (2007) 052509.

[17] A.V. Anisovich, R. Beck, E. Klempt, V.A. Nikonov, A.V. Sarantsev, U. Thoma, Eur. Phys. J. A 48 (2012) 15.

[18] J.A. Niskanen, [arXiv:1610.06013] 1 (nucl-th).

[19] F. Huang, Z.Y. Zhang, P.N. Shen, W.L. Wang, Chinese Phys. C 39 (2015) 071001, arXiv:1408.0458v3 (nucl-th).

[20] M.N. Platonova, V.I. Kukulin, Nucl. Phys. A 946 (2016) 117.

[21] A. Abashian, N.E. Booth, K.M. Crow, Phys. Rev. Lett. 5 (1960) 258; N.E. Booth, A. Abashian, K.M. Crow, Phys. Rev. Lett. 7 (1961) 35.

[22] G. Fälth, C. Wilkin, Phys. Lett. B 701 (2011) 619.

[23] M. Albadaĵo, E. Oset, Phys. Rev. C 88 (2013) 014006.

[24] Y. Dong, F. Huang, P. Shen, Z. Zhang, [arXiv:1702.03658] (nucl-th).

[25] P. Adlarson et al. (WASA-at-COSY Collaboration), [arXiv:1702.07212] (nucl-ex).
